

SCHEDULING OF A FLEXIBLE MANUFACTURING SYSTEM  
FOR BICRITERION OBJECTIVE: TARDINESS AND UTILIZATION

BY

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## **INTRODUCTION**

Approximately 50% of the dollar volume of all manufacturing is in the metal working industry and two-thirds of metal working is metal cutting. In addition, approximately 75% of the dollar volume of metal-worked products are manufactured in batches of less than fifty parts. However, a disproportionate amount of attention has been given to the mass production of a single part type, relative to batch manufacturing. The growth of the industry spawned technological improvements over time which spurred research into developing efficient means of small batch production. One result was the development of flexible manufacturing systems.

### **1.1 EVOLUTION OF FLEXIBLE MANUFACTURING SYSTEMS**

Until the mid-fifties, metal cutting machine tools were manually operated. Requirements for high precision led to the development of numerically controlled (NC), general purpose machine tools. The first NC machining center was developed 1954 at the Servomechanisms Laboratory at M. I. T. using ideas conceptualized by John Parsons in 1948. The early NC machines were paper-tape driven. If the same tool were required, perhaps several consecutive operations could be performed on a particular part. Each operation took a

specified amount of time. However when a new tool was required , it was necessary to halt production to set up the machine tool. Each tool was manually changed, and had to be adjusted for direction and angle. At the same time, the setup procedure might include a refixturing of the part, so that the next operation could be performed on a different section of the part. In addition, a manual part movement or interchange might be necessary.

With the idea of eliminating the setup time and associated set-up cost for a machine tool, the Ford Motor company developed in 1948 the concept of an automatic tool interchange: when required, a particular cutting tool could automatically be taken out of a tool magazine and inserted into the spindle which holds the tool during its use. However it was ten years later that Kearney-Trecker built the first NC machine to utilize the automatic tool interchange.

The next step was to integrate several NC machine tools. The first such system was developed in 1967 by the Sundstrand Aviation Division of the Sundstrand Corporation.

About the same time, Cincinnati Milacron Company announced the Variable Mission Manufacturing system concept.

Initially these two NC systems were digitally controlled by punched tapes. By the time the VMM system was built,(around 1970), the control was by computer.

The first computer-controlled system was built in 1968 by Sundstrand for the Fairfield Manufacturing Company, in Lafayette, Indiana. Although the movement of parts from machine to machine was not automated, the computer replaced punched tape for controlling all machining operations of the machine tools. This was the first directly numerically controlled (DNC) system.

The first DNC integrated manufacturing system to have automatic material handling and storage was built in East Germany and demonstrated at the 1971 Leipzig Spring Fair. About the same time, the Ingersoll-Rand Heavy machining center, consisting of six machine tools interfaced with a conveyor delivery of parts, was installed by Sundstrand in Roanoke, Virginia. Such computer controlled, integrated, batch manufacturing systems have been called flexible manufacturing systems (FMS), computerized manufacturing system (CMS), and variable mission manufacturing systems (VMM).

By 1976, four FMS's were in operation in the U.. S.. In addition one was developed by Cincinnati Milacron, and

another by Kearney-Trecker Corporation for Allis-Chalmers in Milwaukee, Wisconsin. There were several in Europe. Japan leads in the number of FMS's but their systems are generally simpler than those in the United States. The number of new systems is expected to grow rapidly. In fact it is estimated that about 5000 such systems will be in existence by the year 2000.

### **1.2 DESCRIPTION OF FLEXIBLE MANUFACTURING SYSTEM AND ITS COMPONENTS**

A Flexible Manufacturing System can be defined as a computer controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one kind of part at low to medium volumes. The definition highlights the three essential physical components of an FMS :

- \* potentially independent NC machine tools,
- \* a conveyance network to move parts and sometimes tools between machines and fixturing stations,
- \* an overall control network that coordinates machine tools, the parts-moving elements, and the workpieces.

In most FMS installations, incoming raw workpieces are fixtured onto pallets at a station or group of stations set apart from the machine tools. They then move via the

material handling system to queues at the production machines where they will be processed. Part flow begins at the load/unload station, where the raw castings and fixtures are kept. The FMS control computer keeps track of the status of every part and machine in the system. It continually tries to achieve the production targets for each part type and in doing so tries to keep all the machines busy. In selecting parts to be sent into the system, it chooses parts based on the management policies indicated, and for which there are currently empty fixture/pallets or load stations, as the case may be. If an appropriate pallet/fixture is available the loader will get a message at his computer terminal. The part is next sent to the machine.

Once in front of the machine, the computer actuates the transfer mechanisms and the pallet is shifted to the shuttle. The part and pallet wait until the part currently being machined is completed, and then the two parts and their pallets exchange positions. At this stage the proper NC program is downloaded to the machine controller from the FMS control computer. After completing the downloading, machining begins.

The finished part now on the shuttle waits for the computer to send it to its next location. If for some reason the part

cannot go to that destination, the computer checks its files for alternative destinations. If one exists, the computer decides if conditions in the FMS warrant sending the part to that destination. If not the part circulates around the system on the transporter until the destination is available. The computer controls the cycles just described for all the parts and the machines in the system, performing scheduling, dispatching, and traffic coordinations. It also collects statistics and other manufacturing information.

### **1.3 WORKSTATIONS**

#### **1.3.1 MACHINING STATIONS**

The capabilities of an FMS are uniquely defined by the machines it contains. The class of parts to be produced on an FMS usually determines the type of machine or mix of types of machines to be included in that FMS. Presently FMS technology with respect to prismatic parts is more mature than that for rotational parts. The usual choice of machines for prismatic parts is between various brands of vertical and horizontal machining centers and special purpose machines, such as head changers and head indexers. Rotational parts having a length-to-diameter ratio of less than two, such as hubs, or wheels with considerable milling, drilling or tapping, are usually candidates for inclusion in

prismatic part types.

FMS technology with respect to strictly rotational parts bars and shafts is still in its infancy, particularly in the U. S. Standard CNC lathes with both bar and chucking ability, can be integrated to form a rotational FMS, but currently this concept exists only on a smaller scale in flexible manufacturing cells.

Machining centers can be basic horizontal or vertical three-axis machines that process just one side of a piece part. This approach normally requires multiple fixturing passes to complete the manufacture of each piece part. Each pass is treated by a separate part program and may be machined on the same mill or a different one, depending on the work schedule and tool complement of each machine. With the addition of one or two more axes greater piece-part access is gained. This might provide some throughput of a particular FMS.

The family of parts to be produced on an FMS dictates the power, size envelope, and accuracy required of the machining centers. In addition the choice of machining centers may be further limited by considerations of interfaces with the material handling system.

All FMS machining centers have tool storage capabilities,

either in the form of a drum or tool chains. A maximum of 45 to 60 tools in the tool magazine of a machining center is not uncommon.

#### **1.3.2 LOAD AND UNLOAD STATIONS**

The principal requirements of a load unload station include a clean support to the pallet in a position accessible to the material handling system, pallet maneuverability to permit the loader to remove and load piece parts, and a computer terminal for the loader to communicate with the FMS control computer. Most of these stations should preferably be on a raised platform to facilitate flushing of chips after unloading.

#### **1.3.3 MATERIAL HANDLING SYSTEM**

There are two principal forms of part transport: parts must be moved from outside the system into it, and they must be transported within the system. Because mounting of parts on fixtures is, at present, usually a manual operation, movement of parts into the system logically is performed manually. Various types of cranes are employed to maneuver parts too heavy to lift manually. Fork lift trucks and robots are the other possible material handling systems for this stage.

Within the system the principal category of material handling equipment are carts, automated roller conveyors, and robots. Pallets on carts and conveyors are stopped at the right destinations by sensors in the system. The entire functioning of the material handler is by the central computer. Robots are a special consideration for material handling and are generally applicable where spacing between machines is short and workpieces are light.

These are most useful when machines are clustered in a circular work cell so that one robot can serve several machines. They are often used with unfixed parts of rotation.

#### **1.3.4 CONTROL STATION AND ARCHITECTURE**

The mainframe computer is generally in an area remote from the immediate FMS area. Several levels of communication must be available to permit operation and control of the line. Much of this communication takes the form of status reports for each of the machines, the material handling system, and the load/unload stations. Each machine would have its own NC console with display showing machining sequence data.

The FMS control system manages the total combination of

devices in the system that contribute to the automatic operation of the system. This includes all the system components mentioned above. Control of these complex systems is usually built on a hierachial structure. This hierachial control for a FMS is better explained keeping the concepts of a non-FMS shop in mind.

A typical four level hierachial structure is considered in this section. The first level sets the parameters and production goals within which the shop will function. It serves the entire shop, providing database management, material requirement planning, and the master schedule for all production, as well as the business priorities and guidelines for short and long term operation. The second level consists of general manufacturing and support tasks. It also serves the entire shop, providing part process plans, NC programs, tool and fixture design, time standards and machinability data for any part when asked for it. The third level involves general plant coordination, the production control function. At this level parts are scheduled for production according to the master schedule and available shop capacity. The fourth level is concerned with departmental and individual machine operation, the shop floor production requirements. This is like the department foreman making decisions on machine loading based on

equipment availability and due date and other factors.

### **1.3.5 PEOPLE**

When an FMS is operating reliably, the number of people required to maintain its operation can be reduced to a few. Typically there would be one foreman, enough loaders to adequately feed the line, and one machinist to care for as many as half a dozen machining centers. The line foreman oversees the entire operation of the line. He is responsible for maintaining the continuity of the line's production. Apart from these line personnel there are the other supporting personnel such as programmers, process planners, manufacturing engineers, maintenance personnel among others.

Apart from the system components described, there are also other components like the chip and coolant handling systems, inspection systems, and tool cribs.

### **1.4 DIFFERENCES BETWEEN AN FMS AND A CONVENTIONAL MANUFACTURING SYSTEM**

Computer control is the primary difference between the FMS and a conventional manufacturing system. In an FMS, both material handling and tool interchange are computer

controlled. A computer also directs the flow of work, passes instructions for the processing of each of the operation to the appropriate machine tool, and directs the actual machining operations.

A consequence of automatic tool interchange is the small machine set-up time and set-up cost of an FMS which permit less in-process inventory than that of a conventional manufacturing system. In many job or flow shops, each operation is performed on a lot consisting of many parts of particular part type. Each lot moves from machine to machine for processing. The potentially large numbers of parts in each lot could cause large in-process inventories. For this reason, parts are often manufactured to keep stock on hand. In contrast, and FMS generally processes required part types to demand, in lot sizes as small as one. Since in-process inventory is a consequence of lot size, which in turn is a consequence of set-up costs, large in-process inventory presents much less of a problem for an FMS than for conventional manufacturing systems.

Another difference is in the use of pallets and fixtures. The difference is in their use as the automated interface between a part and the material handling system.

#### 1.5 PRESENT STATUS AND FUTURE OF FMS's

Presently, the cost of the direct labor required to run a FMS is much less than for conventional systems. To run the conventional types of manufacturing systems in the U. S. costs an estimated \$115 billion each year in direct labor and direct labor overhead. An FMS requires less direct labor than an equivalent number of stand-alone NC machines. For an FMS producing a variety of part types, approximately one person is required to tend two machines. Fewer people are required for dedicated systems.

The cost of NC machines is decreasing relative to the conventional machines. Hence conventional machines are being replaced by numerically controlled machines. Recent hardware developments may soon eliminate the capacity constraints associated with tool magazines. Presently, each machine in an FMS has an associated tool magazine with room for a maximum of 45 or 60 tools. However, a system has been described which has a large central tool magazine which can hold 605 tools. Other hardware developments which will upgrade FMS performance include sensors which are able to detect dull cutting tools. The dull tools are replaced before they break or before inferior parts are produced.

FMS's are also being applied to processes other than metal cutting such as welding and metal forming. Flexible assemblies are also gaining importance.

In this thesis it is proposed to design and develop a simulation model of a flexible manufacturing system. This system will take into account a majority of the components cited above. It is also proposed to develop a scheduling algorithm and optimize the system parameters.

## CHAPTER II

### LITERATURE SURVEY

The past research in the field of scheduling of flexible manufacturing systems has been the most influential factor in this thesis. O'Grady and Menon (1986) in their tutorial on FMS have categorized the literature on planning and control of FMS into the following categories:

- \* simulation models
- \* queuing theory models
- \* integer programming models
- \* heuristic algorithms
- \* other algorithms and models.

Our literature survey acquainted us with one more approach to the scheduling problem, the Artificial Intelligence/Expert Systems approach. Accordingly we have divided the literature survey into three categories, namely:

- \* Mathematical models
- \* Simulation models
- \* The AI/Expert Systems approach.

## 2.1 IDENTIFYING THE PROBLEMS

Stecke (1985) defined and described the design, planning, scheduling, and control problems in flexible manufacturing systems. A majority of the research after this date has been based on this literature. FMS planning problems have been defined as those decisions that need to be made before the system can begin to produce parts. Scheduling problems on the other hand are problems concerned with the running of the FMS. The FMS planning problems are listed as follows:

- a. From the list of part types for which production orders of various sizes are specified, to choose a subset of part types for immediate and simultaneous manufacture. This part type selection could be based on due dates, machine requirements, or process requirements.
- b. To partition the machines of each type into machine groups. Machines in a particular machine group are said to be pooled when they are identically toolled, and are capable of performing identical operations.
- c. To determine the production ratios at which the selected set of part types should be maintained, over time on the system.
- d. To allocate the limited number of pallets and the fixtures of each fixture type among the selected part

types.

- e. To allocate the operations and associated cutting tools of the selected part types among the grouped machines.

When the FMS planning problems have been solved and all of the cutting tools have been loaded into the appropriate tool magazines, production can begin. These planning problems can be solved sequentially, iteratively, or several simultaneously.

On the other hand, FMS scheduling problems are said to be concerned with running the FMS during real time, once it has been set up during the planning stage. Some of the scheduling problems listed include:

- a. To determine the optimal sequence at which the parts of the selected part types are to be input into the system. Sometimes the part types have to be produced in certain relative ratios, say for assembly purposes. A periodic input sequence might also be appropriate for some types of FMSs. Producing to maintain certain production ratios of part types on the system may be appropriate. Also, a fixed pre-determined input sequence may be appropriate. In other situations a flexible real-time decision concerning which part to input next may be best.

- b. To develop appropriate scheduling methods and algorithms. These scheduling aids can range from simple dispatching rules to complex algorithms or procedures incorporating look-ahead features. Most of the classical literature has been concerned with generating off-line schedules for a manager to try to use. In particular, a scheduling algorithm is often applied to some input data, resulting in a fixed schedule specifying which operations would be performed on which machine tools and when. More appropriate for an FMS might be a real-time, on-line scheduling policy, with scheduling decisions based on the actual state of the system. If the FMS were carefully set up during the planning stage, then a real-time scheduling function might be easier to apply. Perhaps more important during the planning stage, the due date criterion could also apply. This thesis addresses the due date criterion as the most important.
- c. If there are several parts waiting to be processed by the same machine tool, to determine the priorities among these parts. Random processing of parts in batches of size one is commonly referred to regarding FMS scheduling. However, a small amount of intelligent ordering of parts can greatly improve an FMS's performance. While this thesis does not address the

dispatching policy for each machine tool, an innovative loading policy for the system is established.

## **2.2 MATHEMATICAL APPROACH**

Vaithianathan (1982) suggests applying group technology (GT) methods to scheduling problems in a FMS. He defines a "modified flow shop" to be between a job shop and the pure flow shop. In this modified flow shop the jobs enter at any one of several machines, follow any one of a limited number of unidirectional paths and complete their operations in any of several machines. The GT cell he says, typifies the modified flow shop. The FMS also possesses the characteristics of a modified flow shop, with the difference being the flexibility in a FMS.

To reduce the downtime in a FMS, the scheduling procedure should attempt to reduce total setup time by minimizing set-up changeovers. Given the  $n$  by  $m$  loading problem to be solved, Vaithianathan identifies the problem as essentially decomposing the original set of  $n$  jobs to smaller subsets. He suggest statistical clustering techniques based on similarity coefficients, to divide the jobs into sub-groups. Having divided the jobs into sub-groups job shop scheduling rules such as the shortest processing time rule, smallest

remaining slack, and others could be applied to schedule these.

Iwata and Murotsu (1982) treat the production scheduling problem of a FMS as a hierarchical decision making problem which comprises three levels, i.e., selection of machine tools, selection of cutting tools, and selection of transport devices. To solve this scheduling problem the authors suggest a heuristic procedure using decision rules. A decision rule is defined as a rule to select an appropriate machine tool, particular cutting tool, and transport device. The three decision rules presented include:

1. SOTA (Shortest Operation Time with Alternatives considered): This rule is the one which selects both the machine tool and transport device with the shortest time.
2. ESTA (Earliest Starting Time with Alternatives considered): This rule selects the machine tool, particular cutting tool, and transport device, each with large idle time so far.
3. EFTA (Earliest Finishing Time with Alternatives considered): This is a combination of the two rules presented above.

The authors contend that these decision rules are dynamic in

nature compared to the other job shop scheduling rules considered.

Stecke (1983) has formulated nonlinear integer programming problems for two of the five planning problems listed in her earlier article. She has formulated 0-1 mixed integer programming models for :

- a. Machine loading problems and
- b. Machine grouping problems.

The objective of these formulations has been to:

1. Balancing the assigned machine processing time,
2. Minimize the number of movements of the job from machine to machine,
3. Balance the workload per machine for a system of groups of pooled machines of equal sizes,
4. Unbalance the workload per machine for a system of groups of pooled machines of unequal sizes,
5. Fill the tool magazines as densely as possible,
6. Maximize the sum of operation priorities.

While all the objective functions and some of the constraints were non-linear, Stecke linearized the problem and applied a combination of methods to solve these. The linearized formulations were applied to data from an existing FMS. Although the results were not definitive, they

were encouraging, since the grouping and several loading problems were solved optimally and in a reasonable period of time.

Akella and Gershwin (1984) have presented and applied a hierarchical scheduling policy. They have also demonstrated that this hierarchical policy is effective in meeting production requirements, while limiting average work in process. This hierarchical structure is divided into three levels. The policy also is based on capacity discipline. Parts are loaded into the system at rates that are within the current capacity, which is determined by the current set of operational machines. This policy was also applied in this thesis. The middle level is the heart of the scheduler. It determines the short-term production rates, taking the capacity constraints of the system into account. Based on these rates the lower level determines the actual times at which parts are loaded into the system. The middle level uses machine status information and deviation from demand for its computations. It also needs certain long-term information which is supplied by the higher level. This hierarchical policy was successfully tested on a simulated system, based on the IBM printed circuit card assembly.

Shanker and Tzen (1984) have treated the scheduling problem in a flexible manufacturing system as a composite of two interdependent tasks: loading and sequencing. The loading problem addresses the objectives of :

- a. Balancing the workload among machines,
- b. Minimization of system unbalance and the number of late jobs.

The constraints considered include:

- a. Number of tool slots with duplications
- b. Unique job routing
- c. Non-splitting of jobs
- d. Machine capacity.

These constraints do not address the time taken to change tools nor the time taken to get the tools ready for machining. A mixed integer programming problem was presented for the model. Since the formulation is too large to be computationally feasible heuristic algorithms are presented. The first heuristic algorithm balances the workload on the machines, while the second tries to minimize the number of late jobs. Shanker and Tzen are one of the few who have focused their attention on the issue of meeting due dates. Their algorithm for late jobs divides the jobs into four categories and then applies a priority rule to schedule them. A simulation study of the algorithms presented was conducted and results are presented.

Ammons, et al (1985) have developed an optimization model for the loading problem in a flexible assembly. The objectives of their study has been:

1. To balance workstation utilization
2. To minimize the total number of work station to work station job moves.

The constraints considered for the problem include :

1. A large number of components and tools
2. Large tool and component staging capacity at each assembly station
3. Small processing times for individual operations and
4. Static assignment of tools, fixtures and components over a fairly long horizon.

The algorithm for the machine balance objective works by minimizing the difference between the maximum and minimum processing time assigned to the machines, after each assignment of a component.

For the machine visits objective similarity coefficients are computed for all pairs of components and clusters are created. After the clusters are formed, they are assigned to the machines using the algorithm presented. A third algorithm tries to satisfy both the objectives using the

first two algorithms presented above.

The three algorithms were tested using a database based on a production schedule and process charts from a large computer manufacturer. Results are presented.

Oren, et al (1985) have analyzed the performance of flexible manufacturing systems with priority scheduling. The analytical model developed extends the mean value analysis of closed networks of queues with multi product types, various non-preemptive priority service disciplines, and with parallel machine stations. Performance measures derived include the expected throughput per product and per station, utilization of machines and transporters, queueing time and queue length measures for various configurations. Extensive numerical calculations have shown that the algorithm used for solving the problem converges rapidly and shows numerical stability for large models. The paper also illustrates the application of the model to a system with a mixture of FCFS (first come first served) and HOL (head of the line) disciplines which gives insight into various priority assignment policies in FMSs.

Chung (1985) treats the loading problem in a flexible manufacturing system as one with multiple objectives which

are non linear in nature. The model he considers takes into account tool efficiency of the machines. The heuristic approach is felt to provide satisfactory solutions with considerably less computational effort. Accordingly, heuristics have been presented for the two objectives:

1. Balancing the workload on the machines, and
2. Minimizing movements from machine to machine.

Chang, et al (1985) have investigated the effectiveness of a two-phase approximate method for real time scheduling of a flexible manufacturing system. The scheduling algorithm is quasi-real time, in that it does not necessarily reschedule the entire system at each event epoch. Instead, the specific event epoch of a new job arrival triggers a rescheduling of the system. The first phase consists of generation of feasible schedules for  $n$  available jobs, based on  $N$  previously scheduled jobs. Phase 2 selects the optimal schedule combination from the feasible set based on the performance measure. Phase 2 uses an integer programming model to select the schedules for each job so as to optimize according to a specified criterion.

The two-phase method described above was investigated using a simulation model of a flexible manufacturing system. The effectiveness of this method was also compared with the job shop scheduling rules such as shortest processing time,

least work remaining, among others. Results are presented.

Whitney and Gaul (1985) have treated the scheduling problem of flexible manufacturing systems as combination of batching and balancing problem. Batching is treated as a scheduling problem and balancing as a resource allocation problem. A sequential decision algorithm based on optimization of a probabilistic performance criterion, designed to trade off whatever and however many competing attributes may be important in the particular problem. This sequential decision algorithm has been tested against an enumeration algorithm and a random selection algorithm and the results presented.

Carrie and Perera (1986) have studied the impact of tooling considerations in the scheduling and performance of flexible manufacturing systems. This is one of the few articles that take into account the various tooling considerations. Tooling has been studied from the following perspectives:

1. Product variety: Increasing product variety calls for an increased number of tools. For large tool and product variety the tools required may exceed the capacity of the tool magazine. Once this situation arises it will be necessary to change tools from time to time. This is referred to as tool change due to product

- variety.
2. Tool wear: In addition to tool changes due to product variety, there will be tool changes due to tool wear. Since the life of each tool is measured in terms of cutting time, it follows that for any given level of production, the number of tool changes due to wear will be approximately constant.

Based on a real time example it has been concluded that tool change due to product variety accounts for only a small part of the total number of changes. Therefore just-in-time techniques have been suggested, instead of tool scheduling. This thesis considers the tool change time due to tool wear.

Berrada and Stecke (1986) have applied the branch and bound approach to the machine loading problem. The objective of their study has been to balance the work load on the machines while assigning each operation to only one machine. They have formulated a nonlinear integer programming problem. Instead of linearizing this complex problem they have applied the branch and bound algorithm to solve the problem. Results are presented with examples.

Gershwin, et al (1985) have made improvements to the hierarchical scheduling policy of Kimenia-Gershwin, for real

time scheduling of flexible manufacturing systems. The policy presented in this paper is designed to respond to random disruptions of the production processes. In its current formulation, it treats unpredictable changes in operational states of the machines and repairs and failures. Improvements have been carried out in all the levels of the policy and tested for the printed card assembly simulation. The results are found to be promising and suggest the use of this policy for practical situations.

Hall (1986) defines a new class of scheduling problems, for which due dates are specified in terms of the position in which a job appears in an ordered sequence, rather than by the job's identity. The author discusses the algorithmic complexity of such problems. Six such scheduling problems are discussed and solutions are presented for each individual case. Most of these solutions are however based on the job shop rules. The author contends that this class of problems is easier to solve than the one with the classical definition of due dates.

Kusiak (1986) has discussed the design and operation problems of a flexible manufacturing system. He classifies this problem into four levels. These levels include problems on Aggregate planning, resource grouping,

disaggregate planning, and scheduling. The tools and techniques available for solving these problems are:

1. mathematical programming
2. simulation
3. queueing networks
4. Markov process
5. Petri nets
6. artificial intelligence
7. perturbation analysis.

The author also suggests that to make the design and operation of these new systems efficient, one has to consider not only the FMS itself but the interaction with the storage system and the CAD system.

### **2.3 SIMULATION MODELS**

Simulation analysis and design of manufacturing systems is getting more popular on account of its flexibility, and closeness to reality. Mathematical models make more assumptions and are seldom closer to real world situations. In the case of manufacturing systems these mathematical models get too complex to solve. Under such conditions the authors have referred to heuristic solutions. Simulation analysis of flexible manufacturing systems has been based on the simulation studies of job shops.

The operating conditions of a flexible manufacturing system are closer to job shops than flow shops. This fact becomes obvious in the research on scheduling of flexible manufacturing systems.

Rochette and Sadowski (1976) have made a statistical comparison of simple dispatching rules for a particular set of real world job shops. These job shops do not have sophisticated control systems but are restricted by worker availability, job routings, and tight due dates. The measures of performance of the process are the mean flow time and mean tardiness of the jobs. The mean flow time is used as a measure of the work in process. Eight dispatching rules have been simulated and the result statistically analyzed.

Kiran and Smith (1984) have conducted extensive simulation studies of dynamic job shop scheduling. Various job shop scheduling rules have been evaluated in terms of criteria based on :

1. job completion times
2. due dates
3. costs.

The authors have evaluated a number of scheduling rules for each of the above criteria and presented their results.

Stecke and Solberg (1981) conducted a simulation study of the Caterpillar FMS. This flexible system consisted of nine machines, an inspection station, and a centralized queueing area, all connected by an automated material handling system. The study concentrated on the loading policy and the real time scheduling policy for the system. The loading policy was concerned with allocation of operations and tooling to the machines. Five loading policies were considered for this study. Sixteen dispatching rules were evaluated for the scheduling of the jobs. The dispatching rules were selected such that an idle machine could select its next operation from the existing set of parts. Detailed results are presented in this paper. It has been noted that minimizing number of movements can be much better than trying to balance the workload. Both travel time and waiting time is found to decrease considerably if a part stays on its current machine to process its next operation rather than moving. This issue of waiting time has been treated differently in this thesis. A new loading policy has been devised to take care of this idle time.

Fox (1982) has also discussed the application of simulation

to the design and scheduling of flexible manufacturing systems. He suggests the simulation of realistic scheduling procedures, to make the best use of their system. An overview of the FMS software control functions for VARIABLE MISSION systems, simulation and scheduling procedures have been presented.

Nakamura and Salvendy (1985) have compared the effectiveness of human decision making in scheduling a flexible manufacturing system. A real-time interactive simulator was developed for this purpose. The states of the machines and jobs in the FMS were presented to the subjects. The subjects were also acquainted with the operating rules and the objectives of the scheduling. A statistical analysis of the experiment results indicated that :

1. Subjects' decision making is superior to the typical decision rules.
2. Decision making behaviors are highly different between subjects.
3. The look-ahead method contributes to good schedules, but the variance of its reliability is large.

This study goes to show the effectiveness of heuristic procedures.

Schriber and Stecke (1986) have conducted a simulation study

of a flexible manufacturing system taking into account transport time for work in process, contention for transportation resources, machines, and capacitated buffers for work-in process. They have investigated the sensitivity of machine utilizations and part type production rates to the assumptions cited above. They found that when travel time, capacity limited buffers, and contention for automatic guided vehicles and machines are taken into account, achieved machine utilizations and production rates can be from 8 to 29% less than those realized under the aggregate assumptions. This article however does not take into account the time lost due to changing tools. Results are presented in detail.

Choi and Malstrom (1986) have studied twenty-eight scheduling rule combinations on a physical simulator of a flexible manufacturing system. The model constructed consisted of :

- \* an AS/RS,
- \* a parallel storage structure including seven storage areas for raw materials and one storage area for semi-finished parts,
- \* a parallel machine center structure including six identical NC machining centers,
- \* one turning cell including a Mini-mover-5 miniature

- robot, two vertical NC lathes, a washing station, and I/O queues,
- \* overhead conveyers and two lifting ramps for part transfer, and
- \* one CBM 8032 computer and TRS-80 Model III computer for model control.

The evaluation of scheduling rules was done in two phases. Seven part selection rules were combined with four machine center selection rules. These two set of rules were combined to form twenty-eight decision rule sets, which were then evaluated. These twenty-eight decision rule sets were evaluated using six performance criteria. Detailed results of each of the twenty eight combinations of decision rules is provided.

Lin (1986) considers all the operating issues, such as part-mix problem, part-select-machine problem and machine select part problem, as a part of the scheduling problem. The simulation study is based on two storage conditions, namely:

1. FMS with local storage,
2. FMS with common storage.

Two policies for part entry has been designed and four policies for part-select-machine policy. Three job shop rules have been selected as the machine-select part

problem. A combination of these policies have been tested and the simulation results presented.

#### **2.4 THE AI APPROACH**

Apart from mathematical modeling and simulation modeling, artificial intelligence/expert system models are being used to solve the FMS scheduling problems. This approach has gained importance only in the last few years. We also surveyed the articles under this category.

Kusiak (1986) has considered an artificial intelligence and operations research approach to modeling flexible manufacturing systems. He suggests a goal based approach to scheduling, in using the AI approach.

The goal based approach is one in which, given the goal schedule, one has to schedule the parts and machines. In other words a goal schedule, which is the best under any conditions is used as the basis to develop the feasible schedules. Kusiak also compares the AI search methods with the operations research search techniques in this article.

Bruno and Elia (1986) have developed a rule based system to schedule the flexible manufacturing systems. The production scheduling system developed, called "Scheduler", combines

two different techniques:

- \* Expert systems techniques for knowledge representation and problem solving,
- \* Queueing network analysis for fast performance evaluation.

In developing this system the authors have considered :

- \* production constraints
- \* resource constraints
- \* capacity constraints

The scheduler measures the urgency of each of the lots and assigns a priority. The scheduler also enforces resource constraints by making sure fixtures and machines are available. It then enforces capacity constraints by estimating the FMS performance if the lot were introduced. It is only when these two are satisfied that the lot is allowed into the system. The scheduler, which is a knowledge-based module contains a set of rules, and the load evaluation module, which exploits its algorithmic knowledge to provide the scheduler with a set of performance measures to aid decision making. The stopping condition occurs when all the lots have been completed or a pre-defined interval has elapsed.

The scheduler has been written in OPS5, a rule-based, domain-independent production system language. This

sheduler was applied to a hypothetical model and the results presented.

Steffen (1986) expresses the view that artificial intelligence methods are well suited for industrial scheduling problems. In this paper he has made a survey of the AI based scheduling systems. This survey looks at the systems from the following perspectives:

- \* Historical perspective, where the development of ideas has been traced,
- \* Methodological perspective, where AI methods, (such as rule based, heuristic based) used are studied,
- \* Application perspective, where the types of industries that could use these systems are identified,
- \* Implementation perspective, where the success of each of these scheduling systems has been explained.

Kusiak (1987) has discussed the designing of expert systems for scheduling of automated manufacturing. According to the author a typical expert system generates a solution to the problem for which it has been designed. Such an expert system is called a stand-alone expert system. An alternative to the stand-alone expert architecture is the Tandem architecture. The tandem architecture has two distinct components:

- \* Expert system
- \* Model and algorithm.

The tandem architecture takes advantage of artificial intelligence and optimization approaches. The system utilizes the data available and the algorithm to generate a solution. If the solution is acceptable it is sent to the manufacturing system; otherwise the expert system may generate a new set of data for the model.

The solution generated can again take either of the two approaches available, namely:

- \* Goal based approach
- \* Model based approach

In the goal based approach the scheduling problem can be formulated as follows: Given the goal schedule, schedule resources of the machining system to minimize the deviation between the goal schedule and the current schedule.

In the model based approach, the models could be either single or multi-model approach. Designing the tandem architecture expert system is discussed in detail in this article.

## **2.5 PARTS GROUPING PROBLEM IN FMS**

Stecke (1985) has identified part type selection problem and the grouping problem as being a planning problem. Part grouping among the available parts to meet the production plan has been one of the major problems for researchers. We came across a number of articles on this aspect of FMS planning. Some of the important articles that were referred to, are summarized. Applying GT techniques for part grouping has been popular in practice. However, better methods and algorithms have also been developed.

Kusiak, et al (1985) have presented a network formulation for the grouping problem in flexible manufacturing systems. The approach presented enables one to fix the number of groups, based on the number and types of fixtures. The second important factor taken into account is the size of the group, as it affects the complexity and analysis of the scheduling problem. A numerical example has also been presented.

Hwang (1986) presents a constraint-directed method to solve the part selection problem in a flexible manufacturing system. Hwang has identified three factors as important to machine balancing, in the part selection stage:

1. the number of tool magazine slots in the system,

2. the due dates for each part,
3. the total processing time.

In this article he considers the tool magazine constraint and part selection. He contends that if the production order is fixed until it is finished, the first translation of the objective is to minimize the total time required to process the whole order. In the deterministic situation, we can assume the total production time consists of only the setup time and the machining time. Then the second translation of the objective is to minimize the time between two successive batches and the time within each batch. The objective related to part selection is to minimize the time between batches. The time spent between batches is the time of setup. If the setup time is uniform from batch to batch, minimizing the total setup time is equivalent to minimizing the number of batches. This means maximizing the number of part types in a batch. Hwang has also presented a mathematical programming formulation for this model. The drawback of this model is that parts that require a large number of tools will be selected later. If incoming orders are permitted to be mixed with the unselected parts of the current order, parts requiring large number of tools may never be selected. This calls for the introduction of due dates, in part selection.

## **2.6 SIMULATION AND DESIGN OF FLEXIBLE MANUFACTURING SYSTEMS**

The capital costs involved in the purchase, commissioning, and running of flexible manufacturing systems is so high that purchasers want to ensure proper design. Simulation is probably the only authentic tool available right now that will assist in design, validation, and analysis of flexible manufacturing systems successfully.

Carrie (1986) has detailed the experience of a Scottish firm in the design and purchase of the flexible manufacturing system. The study brings out the advantages of simulation modeling of the system before commissioning. This flexible manufacturing system being commissioned, was for the manufacture of complex castings. The preliminary design stage led to the following principal assumptions:

1. One pallet (storage) stand would be used for parts queueing to go on to a machine, and the other to be used for parts getting off the machine,
2. The load/unload area could be regarded in the same way as any other workstation, except that new castings arrive from outside the system,
3. The availability of fixtures, pallets, and tools would not influence the system performance,
4. The system would not suffer breakdowns,

5. There would be only one set of part types in the system.

In running this model it was found that the system could become so congested that it became impossible to move castings away from the load/unload area, because the on-queue pallet stands at the required machines were already occupied by castings. These castings could not go onto the machine because the machine table was occupied by a casting waiting to go to the off-queue pallet stand, which was itself occupied by a casting awaiting moving to the load/unload area. This was not an error in the program but poor designing of storage areas. This error was corrected by permitting pallet stands to serve either as an on-queue or an off-queue, not restricted to one or the other. Carrie also lists the simulation languages available and details of digital simulation.

This aspect of congestion was given due consideration in this thesis and an innovative design was adopted for the same. Details are indicated in the next chapter.

While there have been many publications on simulation modeling for design of flexible manufacturing systems, we have just detailed the one by Carrie, as it presents an useful analysis on design and layout for storage areas.

Law (1988) has also simulated a computerized manufacturing system and made a detail analysis. The outcome was a large saving for the user of the system, as also effective utilization of material handling system.

In the next chapter we define the problem considered. This problem was developed based on the past research, and some of the factors missed.

## CHAPTER III

### PROBLEM STATEMENT

The previous chapter gave us an indication of the importance of scheduling a flexible manufacturing system for proper utilization of the system. A considerable amount of research has been carried out in this field in the last decade. However, research has concentrated on two objectives:

1. Workload balance on the machines
2. Minimum number of machine visits, by a product. The idea here is to reduce the traveling of the part within the system.

While there is a lot of opportunity for research in this field, the question we wanted to address was, "What if I were the manager of a flexible manufacturing system?"

Smith, et al (1986) conducted a survey of the 22 flexible manufacturing system operators in the United States. They investigated various aspects of running a flexible manufacturing systems. Scheduling was found to be one of the most important aspects for the FMS operators. The survey indicated the following:

1. For more than 59% of the FMS owners, meeting due dates was the primary objective, of scheduling.

2. About 44% indicated that machine utilization was their second important objective in scheduling the system.
3. Conveyors, and not AGVs, were the most popular form of material handling system.
4. More than 75% of the systems were being used for metal cutting operations.

The authors conclude their article with saying, "There are very few procedures described in the literature that address the due date problem. It is also interesting to note that some of the criteria, like minimizing the flow time and balancing machine usage, which have been in the FMS scheduling literature received little support from FMS users. One can observe from the responses to the questions related to criteria that both minimizing flow time and balancing machine usage seem to be relatively insignificant for scheduling considerations by the FMS users."

This thesis tries to address the practical, industry oriented problems of scheduling a flexible manufacturing system. The primary objective of scheduling the flexible manufacturing system in this thesis will be:

1. To meet due dates
2. Maximize machine utilization.

These objectives were considered to be important from the system manager point of view.

Most of the literature on scheduling of a flexible manufacturing system also assumes tooling considerations to be near perfect. While NC machines do have multiple tooling capacity, and automatic tool changing capability, tooling is still a major constraint. A. S. Carrie and D. T. S. Perera (1986) have reported that with increasing product variety, tool variety also increases. This they say even might exceed the tool magazine capacity. They say that it is the tool change due to tool wear that is a major consideration. Since tool wear is based on cutting time, it follows that for a given level of production, tool change on account of wear will have to be considered.

There are two aspects of tooling which we thought affects the scheduling and machine utilization aspects of a flexible manufacturing system:

1. Tool wear
2. Tool downloading

Most NC machines these days are tooled with tungsten carbide tools. The average life of tungsten carbide indexable inserts is reported to be 5 to 30 minutes (Ref: Krupp Widia manual). This could be further extended to 60 minutes, depending on the cutting parameters and the surface finish required. In spite of a multiple tool magazine, tool change time due to tool wear does take effect if the system is going to be run over three shifts and two hundred days.

This thesis considers the tool change time due to tool wear. Analysis of results leads to interesting conclusions on this.

Tool changing is automatic in an NC machine. But considering the operations possible on a part, the variety of parts, the number of parts, and the different types of tools that need to be used on a three shift FMS, calls for another time component to be considered. This is the time lapse between the previous tool going off the toolhead and the required tool being moved from the tool magazine. A nominal time component was considered for this time lapse, and was called as the tool downloading time. It was also assumed that tool scheduling for the individual tool magazines, getting the tools ready for use, and other aspects were carried out in a separate area, and were not influential in terms of scheduling.

We could sum the problem considered in this thesis as: "To schedule the flexible manufacturing system to satisfy the dual objective: "meet due dates and maximize utilization." This would also take into account the time lost due to tooling considerations, apart from the others.

## CHAPTER IV

### MODEL DESCRIPTION AND OPERATING RULES

It was proposed to develop a flexible manufacturing system capable of handling a moderate variety of parts. Since it was our aim to keep this thesis industry oriented, our model design was also based on this belief.

#### 4.1 SELECTION OF MACHINES

Smith, et al (1986) reported that 75% of the flexible manufacturing systems were being used for metal cutting operations. We decided therefore to build our model on these lines. It was our aim to keep the machines as flexible as possible, in terms of process capability. These two considerations led to the choice of the most versatile machines: NC machining centers.

The Charles Stark laboratory book on flexible manufacturing systems indicates that 3 to 12 machines would be the most ideal for an FMS. Accordingly it was decided to have three machining centers. These machining centers were assumed to have the following characteristics:

1. Capability to performing a variety of operations such as drilling, tapping, reaming, milling, and boring.

2. Automatic tool changing capability, under computer control.
3. Only one table on which the workpiece could be set up.
4. Thirty two tool magazine capacity.

#### **4.2 MATERIAL HANDLING SYSTEM**

Smith, et al (1986) also reported that the majority of the FMS operators used conveyers as the major material handling system. Automated conveyers were considered to be more versatile than AGVs by these users. Accordingly we decided to use an automated conveyer as the material handling system. This conveyer would be accessible to various sections of the system. The operating conditions for this is detailed in the following sections.

Robots were the second set of material handlers considered. It was proposed to use three robots for refixturing, reorienting the parts between operations. These robots were not to be used for any other functions.

Pallets were the third kind of material handling equipment to be used in the system. The design of these pallets was to be based on the part types. The number of pallets available at any point of time was to be based on the loading policy decided by the management. These are detailed in the following chapters.

#### **4.3 STORAGE AREAS**

Carrie (1986) has given a detailed description of the problems faced by a Scottish firm while designing a flexible manufacturing system. In running their model, the designers found that the system could get congested due to the poor design of storage areas for parts. Though a solution was found for this problem, it did cost time and money. In this thesis due consideration was given for the design of storage areas. It was decided to have separate storage areas for:

1. Parts waiting to be scheduled
2. Parts partially processed

It was also decided to keep these away from the machining area. This design helped us to prevent any kind of congestion that could occur on the conveyer. There was a time delay in terms of traveling time from the storage area to the machining area. This design also keeps the machining area operational all the time. Accordingly the storage areas were named as:

1. Raw material storage
2. Work in process storage.

#### **4.4 OPERATING RULES FOR THE SYSTEM**

Operating rules for each component of the flexible

manufacturing system was decided. The details of these are as follows:

#### **4.4.1 PRE-LOADING OPERATIONS**

1. All the required paper work for every order will be completed before routing the parts for manufacturing.
2. Due date for each order will be fixed and this will be indicated in the factory order.
3. Parts will be available in a condition where in they can be directly scheduled and machined. Details of these conditions follow in the next few sections.

#### **4.4.2 LOAD AND UNLOAD AREAS**

1. Load/Unload areas will have manual operators. These operators will be responsible for loading/unloading the parts to/from the pallets.
2. The number of operators to be allowed is a decision of the management and does not affect the operation of the system. It is assumed that personnel scheduling for this area is always ensured.
3. The number of pallets available for loading depends on the loading policy being followed. However, it is assumed that the right type of pallet for a part will be available. The restriction on the number of pallets

does not affect the, type of pallets.

4. The conveyer will not be congested at any point of time.

After our analysis of the results obtained, we felt that assumption 4 on the conveyor availability was unrealistic. Accordingly the simulation was re-run with conveyor constraints. Results are presented.

#### **4.4.3 MACHINING AREA**

1. Machines will be grouped together in an area called the machining area.
2. The machining centers are capable of performing milling, drilling, reaming, and tapping.
3. The machines are free of failures and breakdowns. However preventive maintenance will be carried out regularly. Time considerations for this is detailed in the following sections.
4. Tool scheduling will be carried out by planning personnel. The right kind, type, and number of tools will be available for a given order.
5. The number of jobs admitted into the machining area will depend on the loading policy being followed.
6. Reorientation or refixturing of semi-finished parts will be carried out in an area away from the machining area.

7. The machines will not be available for operation when preventive maintenance and tool changing is being carried out.
8. The right programs will be downloaded to the machining centers by the central computer.

#### **4.4.4 MATERIAL HANDLING SYSTEM**

##### **CONVEYERS**

1. There will be no limit on the capacity of the conveyer in terms of the number of jobs it can handle at any time. This assumption was amended and the system performance studied with capacity constraints on the conveyor.
2. The central computer will control the safe operation of the conveyer. This includes a non-collision movement for the parts on the conveyer.
3. The conveyer will be connected to all the sections of the flexible manufacturing system.
4. There will be no restriction on the shape of the parts that can be handled by the conveyer. There will, however, be a restriction in terms of the weight of the parts that could be handled.
5. The conveyer also undergoes preventive maintenance and is free from failures otherwise.

## ROBOTS

1. Robots will be used only for reorienting/refixturing parts.
2. These robots will be available only at the refixturing area.
3. Robots can handle only one part at a time, and they will be suitably programmed beforehand.
4. The shape of the part will not be a restriction on the capability of the robot.
5. Robots will be free from failures.

### **4.4.5 STORAGE AREAS**

#### RAW MATERIAL STORAGE AREA

1. This storage area will handle only parts that are waiting to be scheduled.
2. Parts will be stored in terms of their order number and can be retrieved only by specifying the order number.
3. There will be no restriction on the number of parts the storage area can handle at any time.
4. The central computer will keep track of the location of a part within the storage area.

5. The storage area will be accessible through the conveyer.
6. The parts from this storage area will go to the loading station to be loaded on to the correct fixture.

#### IN-PROCESS STORAGE AREA

1. This storage area will handle only parts that are semi-finished and are waiting for some component of the system to become available.
2. These parts will be dispatched from the storage based on their priority, if any. Otherwise the dispatch policy will be first-in, first-out (FIFO).
3. The parts will continue to be on the fixtures while in this storage area.
4. There will not be any restriction on the number of parts the storage can handle at any point of time.
5. The central computer will control the functioning of this storage area.
6. This storage area will be away from the machining area. As this storage area serves as a waiting area for semi-finished parts, it will be accessible by the conveyer.

## CHAPTER V

### PRE-PLANNING FUNCTIONS

As the entrepreneurs of this study we concerned ourselves with the preliminary functions which included decisions about:

1. The part families
2. Process details of these part types
3. Machining time for each of these part types
4. Tooling requirements of these part types.

#### 5.1 DEFINITIONS

Before we present the details of parts and tooling requirements, we define some of the terms repeatedly used in this thesis:

PART TYPE: These are the parts to be machined in the simulated flexible manufacturing system. Twenty-five parts were selected for this thesis.

PART FAMILIES: Parts with similar manufacturing and design features were grouped together to form part families. The twenty-five parts were classified into five part families. For example, part family 1 were tool holders with similar insert pocket design. These parts had common design and

manufacturing characteristics.

TOOL GROUP: The various kinds and sizes of tools were formed into smaller groups called tool groups. These smaller groups were made up of tools of similar cutting capabilities.

TOOL CHANGE TIME: This is the time spent in changing the wornout tools in the tool magazine of a machining center. This changing was for a particular tool group. Details follow.

TOOL DOWNLOADING TIME: This is the time spent in the movement of the tool from the tool magazine to the tool head.

DUE DATE: This is date by which the part should be completely machined. In other words, this is the date on which the part should leave the flexible manufacturing system. This date is fixed for every part by the planning personnel.

## 5.2 PART TYPE SELECTION

Smith, et al (1986) indicate that 3 to 20 part types were manufactured by nearly 15% of the FMS operators. Since our FMS model consisted of only three machining centers we

decided to keep the number of part types to about 20-25. These part types were to be divided into 5 part families.

The moderate size of the FMS model also suggested that we consider average sized parts for manufacture. Our earlier experience in the manufacture of cutting tools resulted in our selecting 25 part types among cutting tools, jigs, fixtures and clamps. Details of these part types are indicated in Appendix I.

### **5.3 PROCESS REQUIREMENTS**

Having determined the part types to be manufactured, the next step was to decide the process requirements. These process requirements were decided part familywise. The details are as follows:

**Part family 1** Toolholders

Number of parts 6

Processes Face milling - 4 sides

End milling - Insert Pocket

Drilling

**Part family 2** Groove shanks

Number of parts 4

Processes Face milling - 4 sides

End milling - 2 sides of the pocket

### Drilling and Reaming

Part family 3      Chuck jaws

Number of parts    6

Processes             Face milling - 4 sides of shank  
                       End milling - grooves  
                       Drilling

Part family 4      Vise

Number of parts    5

Processes             Face milling of plate  
                       End milling of circular groove  
                       End milling of U groove  
                       Drilling and Reaming

Face milling and end milling of the heavy duty vise must be carried out at very low feeds, due to the thinness of plates.

Part family 5      Pump lock jig

Number of parts    4

Processes             Base plate:  
                       Face milling  
                       Top plate:  
                       Face milling and Drilling  
                       Rear plate:  
                       Face milling and drilling

#### 5.4 MACHINING REQUIREMENTS

Having determined the process requirements, the next stage was to calculate the machining times for each of these part types. Since we could not obtain data on machining times for the part types considered, the following steps were adopted to calculate the machining times:

1. The process requirements were further classified into roughing operation and finishing operation. Each one was treated as a separate operation. For each of the part types the total number of operations required to completely machine it was also recorded. This classification was required because each of these required different cutting parameters. From the management point of view this meant different tool requirements and tool scheduling.
2. For each of the operations of every part type, the depth of cut, chipload, and number of passes required was decided. It was assumed that the amount of material to be removed would not require more than two passes for one operation.
3. The feed in inches per minute was determined from the "Feed and Speed chart for CNC programmers ", produced by Cecil Richardson. These values were different for roughing and finishing operations.

Since the dimensions of the parts were already known, and the feed used was in inches per minute, the machining time was calculated as follows:

feed : x inches/minute

length of cut: y inches

time required for machining the length:

$y/x$  inches/inches/min

= t mins.

A numerical example follows. Appendix 1 indicates the machining times for every operation of each part type.

#### NUMERICAL EXAMPLE

Part type: 1

Size: length: 5"

width: 1"

Shape: Rectangular

Number of operations: 7

Operations 1, 2, 3, 4: Face milling (roughing+finishing for  
each of the four sides)

5 & 6: Drilling

7: Reaming

Operation 1 feed = 2.5 inches per minute for roughing  
= 0.625 inches per minute for finishing  
tool feed time =  $12/6.0 = 2$  minutes  
cutting time =  $5/2.5 = 2$  minutes (roughing)

$$5/0.625 = 8 \text{ minutes (finishing)}$$

$$\text{total} = 12 \text{ minutes}$$

Operation 2 (another side of shank) = 12 minutes

Operation 3 (third side of shank) = 12 minutes

Operation 4 (fourth side of shank) = 12 minutes

Operation 5 feed = 0.018 & 0.013 inches per minute

$$\text{cutting time} = 0.5/0.018 + 0.5/0.013 = 66$$

Very low feeds have been considered for operation 5, because of the close tolerances that need to be maintained on the dimensions. This operation is for milling of the insert pocket, which has a number of close tolerances and various angles to be maintained.

Operation 6 Drilling : 5 minutes

Operation 7 cutting time = 2 mins

Total time required for part type 1 : 122 mins.

The following assumptions were made while calculating machining times:

1. The material of the parts is C1018 steel.
2. The shank is cut to the correct length.
3. The parts are inspected and ready for machining.

Appendix 2 indicates the setup time considered for each of the part types. This setup time is the time required to

refixture or reorient the parts between operations, and does not include the setup time before the part entered the system.

## CHAPTER VI

### PLANNING FUNCTIONS

In this chapter we concentrate on the planning functions to be considered before trying to schedule the flexible manufacturing system. The planning functions considered include:

1. Effective number of shifts and total time of operation of the system,
2. Due date calculations, policy decisions,
3. Part mix policy to be followed,
4. Tool size and classification of tools into groups,
5. Ratio of tools to be maintained on machines,
6. Tool wear time calculations and tool down time to be considered.

#### 6.1 WORKING HOURS FOR THE SYSTEM

It was decided that the system will be operational for 20 hours per day over three shifts. For every shift one hour was allocated to get the system hardware and software set up, with twenty minutes as the effective break. For one day this worked out to four hours, resulting in an effective operation time of 20 hours for the system. The system would be available for 5 days a week. It was assumed that any

preventive maintenance would have to be carried out during the weekend or during the four hour idle time.

## **6.2 DUE DATE CALCULATION**

The marketing department would have made a commitment on the delivery date to the customer and indicated it in the factory order. But from the production point of view a due date had to be calculated by the planning personnel in order to meet the customers delivery date, while allowing for possible delays. This calculation of due date was to be based on the available machining capacity. Parts that could not be accommodated in one scheduling period were to be shifted for the next scheduling period. This policy was simulated in a different way. Parts that could not be accepted for one scheduling period were just rejected or removed from the system.

For the given scheduling period the total available machining time for that period was determined. As each part was admitted into the system, the available machining time was reduced by the machining time required for that part. Thus the current available machining time was always available and used for due date calculation. This also ensured that the due date for the part was purely based on the available machining capacity, and was achievable.

Certain rounding off decisions had to be made in calculating due dates. For this thesis it was assumed that all parts that were due after the 16th working hour of the day had their due dates fixed for the next working day. This rounding off factor had to be included in the program to facilitate the collection of data. Without the rounding off, parts that were due the later half of the day were also getting a due date assignment for that day. Since these parts were being completed the next day, it portrayed the wrong lateness performance. A part that cannot be completely machined on one day is bound to go into the next for machining. By treating the 16th hour as a cutoff time to assign that day as a due date, we were making the due date assignment more realistic and reasonable.

A different approach was also maintained to keep track of the dates. Calendar dates were not followed. Instead a production day calendar was used. The first working day of the year was treated as day # 1. From then on, each working day was incremented upto the last working day of the year. Weekends were not treated as working days and were never considered. Thus the last possible date will be equal to the number of working days (200 or 202). For example if today was Monday and day # 1, then day # 10 would be the Friday of the next week (week 2), as there are only five

working days in a week. This method required us to keep track of only one figure, that of day count. The week, or the month never came into the picture. This system was found to be simple and adequate.

#### **6.3 PART MIX PROBLEM**

The part mix problem itself an area of interest for research. Since we had decided to have 25 part types with the number of operations on the parts ranging from 7 to 13, and the machining times varying from 122 to 300 minutes, a safe part mix policy was adopted. We gave equal representation for each of the part types during a scheduling period. Accordingly, a function that would assign an equal ratio of the parts into the system was used. Details are indicated in the following chapters. It is our suggestion that the part mix problem is a good topic for research by itself, and should be pursued.

#### **6.4 TOOLING DECISIONS**

Appendix I indicates the sizes and types of tools to be used in the manufacture of the 25 part types considered. The problems being considered in this section include:

1. The ratio and number of each type of tools required on every machine.

2. The tool wear time and the tool changing policy.

The variety of tools required, and the different sizes for each variety, was considerable. Hence it was decided to classify the range of tools into four broad groups. This would make it easier to calculate and keep track of the tool wear time. Once the tools were divided into one of the four groups, all calculations and reference were group based.

#### **6.4.1 TOOL GROUP CLASSIFICATION**

We see from Appendix I that face milling is the major operation from an overall point of view. We found that we would require at least 4 sizes of milling cutters for the part range considered. Apart from these endmills of different sizes, drills and threading tools were also to be used.

Tool scheduling for a given set of part types is a topic for research, by itself. We recommend that the subject of tool scheduling for this system should be treated as a research topic and pursued. A tool scheduling algorithm could probably be developed. However, for this thesis we decided not to go into too many details of tool scheduling. We followed a simple logical method to schedule the tools on the machines.

The entire range of tools were divided into four groups as indicated below:

1. Face milling cutters of 3" and 5" diameter
2. Face milling cutters of 12" and 15" diameter
3. Endmills
4. Other tools

This classification of tools is based on the design and size of adaptors required on the tool magazine. The tool change time for tools within a group is considered to be the same. The ratio of tools on each machine is based on the number of times each tool is used. For example, if we assumed that only part types of part family 1 were manufactured then (this is only an illustration):

- |                              |          |
|------------------------------|----------|
| * tool group 1 would be used | 24 times |
| * tool group 3 would be used | 6 times  |
| * tool group 4 would be used | 6 times  |

This would mean the ratio of tools on each machine would be 4:0:1:1 for each of four groups. In effect there would be 24 tools of group 1, 6 each of group 3 and 4, and none of group 2. The same logic was extended to all the part types considered for this thesis. This calculation gave us an indication that we should maintain the ratio of tool groups on each of the machining centers as follows:

- |                                  |           |
|----------------------------------|-----------|
| 1. Tool group 1                  | 8 cutters |
| Face milling cutter 3" diameter: | 6 cutters |

	Face milling cutter 5" diameter: 2 cutters
2. Tool group 2	8 cutters
	Face milling cutter 12" diameter: 6 cutters
	Face milling cutter 15" diameter: 2 cutters
3. Tool group 3	10 tools
4. Tool group 4	6 tools

This decision on the ratio of tool groups on the machines also helped us to calculate the time lapse between tool changes due to tool wear.

Only tungsten carbide tools would be used in the FMS considered. The average life of a carbide insert considered in this thesis is 50 minutes. It was assumed that the wear on all the inserts on any of the tools would be uniform. For example, in the case of face milling cutters this would mean that all the six inserts in one cutter would have the same amount of wear. This allows all six inserts to be changed at a time. This assumption is practical and also applied in industry for tool changes.

Therefore, for tool group 1, with 8 cutters on every machining center, tools will have to be changed every 400 minutes of cutting time. This time interval takes into account the wear on each cutter/tool. Based on similar calculations the following time intervals for each of the

groups was decided:

- \* tool group 1 every 400 minutes
- \* tool group 2 every 400 minutes
- \* tool group 3 every 740 minutes
- \* tool group 4 every 640 minutes

For each of the above tool groups, and for each of the machining centers the time taken to carry out the tool change was decided based on experience. These values are as follows:

- \* tool group 1 : 16 minutes
- \* tool group 2 : 16 minutes
- \* tool group 3 : 20 minutes
- \* tool group 4 : 16 minutes

When the system was run for a longer period of time the time lost due to tool changing was indeed a matter of concern. The system was capable of keeping track of the usage of each of the tool groups and initiate changing action on its own. The concerned machine was not available for machining during this time.

To save on idle time we assumed that instead of replacing inserts on each of the cutters, a set of fully assembled tools of that group would be replaced. This assembling of the substitute tools would be carried out previously, and would not affect the operation of the system.

#### **6.4.2 TOOL DOWNLOADING TIME**

Machining centers are equipped with automatic tool changing capability. Even though tool movement from the tool magazine to the toolhead is automatic, there is indeed a time lapse between the removal and replacement of the tools. When the number of part types being manufactured is large, the variety of tools used is large for a system operated for three shifts and 200 days, this nominal time lapse becomes a matter of interest and concern. This time adds to the non-machining time of the machining center and in turn affects the utilization. We assumed a value of 1.5 minutes as the time lapse between removal and replacement of tools on the machining center. Results obtained in this simulation study confirmed this aspect of non-machining time to be important. Details are presented in the following chapters.

## CHAPTER VII

### THE SCHEDULING ALGORITHM

The objective of this thesis was to schedule the flexible manufacturing system to

1. Meet the due dates,
2. Maximize machine utilization.

This chapter concentrates on the scheduling algorithm developed by us to schedule the system, and some of its features.

O'Grady and Menon (1984) in their tutorial on flexible manufacturing systems, have indicated that the scheduling problem in a flexible manufacturing system could be treated as a multiple criteria decision making problem. For this thesis we treated the scheduling problem as a multi-criteria decision making problem. We applied the "Technique For Order Preference By Similarity to Ideal Solution" (TOPSIS) method. Details of the method follow.

#### 7.1 DEFINITIONS

Before we provide with the details of TOPSIS methods, we define some of the key words repeatedly used.

Attributes: Performance parameters, components, factors, characteristics, and properties are synonyms for attributes. An attribute should provide a means of evaluating the levels of an objective.

Criteria: A criterion is a measure of effectiveness. It is the basis for evaluation. Criteria are emerging as a form of attributes or objectives in the actual problem setting.

Decision Matrix: A MADM problem can be concisely expressed in a matrix format. A decision matrix D is a [mxn] matrix, whose elements  $X_{ij}$  indicate evaluation or value of alternative A<sub>i</sub> with respect to attribute X<sub>j</sub>.

## 7.2 TECHNIQUE FOR ORDER PREFERENCE BY SIMILARITY TO IDEAL SOLUTION (TOPSIS)

Hwang and Yoon (1981) have classified a number of MADM solution methods and explained them. One of the methods, developed by them is the "Technique for order preference by similarity to the ideal solution", called TOPSIS. This method is based upon the concept that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative ideal solution.

Assume that each attribute has a monotonically increasing (or decreasing) utility; then it is easy to locate the ideal solution which consists of all best attribute values attainable, and the negative-ideal solution composed of all worst attribute values attainable. One approach is to choose an alternative which has the minimum Euclidean distance to the ideal solution. It is argued that this alternative should be farthest from the negative-ideal solution at the same time. TOPSIS considers the distances to both ideal and negative-ideal solutions simultaneously by taking the relative closeness to the ideal solution. In the next section we describe the algorithm for this method.

#### THE ALGORITHM

TOPSIS evaluates the following decision matrix which contains m alternatives and n attributes:

$$D = [x_{ij}] \quad i = 1, 2, \dots, m, \quad j = 1, 2, \dots, n$$

TOPSIS assumes that each attribute in the decision matrix has either monotonically increasing or monotonically decreasing utility. The following are the steps of the algorithm.

Step 1 Construct the normalized decision matrix: This process transforms the various attribute dimensions into

non-dimensional attributes, which allows comparison across the attributes. One way is to take the outcome of each criterion divided by the norm of the total outcome vector of the criterion at hand. An element  $r_{ij}$  of the normalized decision matrix  $R$  can be calculated as

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$$

consequently, each attribute vector has the same unit length of vector.

Step 2 Construct the weighted normalized decision matrix: A set of weights  $w = (w_1, w_2, \dots, w_n)$ , whose sum is equal to 1, is accommodated into the decision matrix in this step. The weights are provided by the decision maker, based on his evaluation of the attribute importance. The weighted normalized matrix is calculated by multiplying each column of the already normalized matrix with its associated weight.

$$V = [w \ r_{ij}] \quad i=1,2,\dots,m, j=1,2,\dots,n$$

Step 3 Determine ideal and negative-ideal solutions: Let the two artificial alternatives  $A^*$  and  $A^-$  be defined as

$$\begin{aligned} A^* &= \{ [\max_i V_{ij} \mid j \in J], [\min_i V_{ij} \mid j \in J'] \mid i = 1, 2, \dots, m \} \\ &= \{ V_1^*, V_2^*, \dots, V_j^*, \dots, V_n^* \} \end{aligned}$$

$$A^- = \{ [\min_i V_{ij} \mid j \in J], [\max_i V_{ij} \mid j \in J] \mid i = 1, 2, \dots, m \}$$

$$= \{ \underline{\underline{v}}_1^-, \underline{\underline{v}}_2^-, \dots, \underline{\underline{v}}_j^-, \dots \underline{\underline{v}}_n^- \}$$

Then it is certain that the two created alternatives  $\underline{\underline{A}}^*$  and  $\underline{\underline{A}}^-$  indicate the most preferable alternative (ideal solution) and the least preferable alternative (negative-ideal solution), respectively.

Step 4 Calculate the separation measure: The separation between each alternative can be measured by the n-dimensional Euclidean distance. The separation of each alternative from the ideal one is then given by

$$\underline{s}_i^* = \sqrt{\sum_{j=1}^n (\underline{\underline{v}}_{ij}^- - \underline{\underline{v}}_j^-)^2} \quad i = 1, 2, \dots, m$$

Similarly, the separation from the negative-ideal one is given by

$$\underline{s}_i^- = \sqrt{\sum_{j=1}^n (\underline{\underline{v}}_{ij}^* - \underline{\underline{v}}_j^*)^2} \quad i = 1, 2, \dots, m$$

Step 5 Calculate the relative closeness to the ideal solution: The relative closeness of  $\underline{\underline{A}}_i$  with respect to  $\underline{\underline{A}}^*$  is defined as

$$c_i^* = \frac{\underline{s}_i^-}{(\underline{s}_i^* + \underline{s}_i^-)}, \quad 0 < c_i^* < 1, \quad i = 1, 2, \dots, m$$

Step 6 Rank the preference order: A set of alternatives can now be preference ranked according to the descending

\*  
order of C<sub>i</sub>.

### 7.3 TOPSIS AS APPLIED TO SCHEDULING THE FMS

In this section we describe the TOPSIS method as applied to schedule the flexible manufacturing system simulated.

#### 7.3.1 ATTRIBUTES

Our primary objective (criterion 1) in scheduling the system was to meet the due dates of the jobs, and the secondary objective (criterion 2) was to maximize machine utilization. Three attributes of the jobs were important for these two criteria:

1. Due dates of the individual jobs
2. The number of operations for each of the jobs. This was important because more operations, meant more time spent in tool changing, fixturing, and possible travel time. For the parts considered the number of operations varied from 7 to 13.
3. The most important factor affecting utilization was the time taken to machine the part. For a job with a close due date, smaller machining time would be advantageous, or from the management point of view it would be easier to meet the due date.

These above three factors were treated as the attributes for

each of the alternatives. Each of these attributes were weighted on a relative scale. The sum of their relative weights added to 1. The weights given to each of them was varied and used to analyze the behavior of the system. Since the due date criterion was more important to us most of the analysis was done with a higher importance to the due date attribute.

### **7.3.2 DECISION MATRIX**

The decision matrix used in the TOPSIS method for scheduling the flexible manufacturing system considered the jobs as alternatives. These jobs (alternatives), formed the rows of the matrix. The three attributes (due date, number of operations, and the machining time) formed the columns of the matrix. In effect there were "n" rows of jobs, and "m" columns (3 in this case) of attributes for each of the jobs.

### **7.3.3 Positive Ideal Solution**

The positive ideal solution is defined as "the most preferable" solution. For the scheduling problem considered, this would be "the most suitable" job, (to meet the objectives). We define the "most suitable" job that will satisfy the due date criterion as the one which has the closest due date among the jobs to be scheduled. This selection is purely based on the assigned due date. For

example, if there were two jobs waiting to be scheduled and job 1 was due on day # 3 and job .2 on day # 6, job 1 would be preferred. In order to meet this due date, it will be desirable if the job had a minimum number of operations. A minimum number of operations will reduce the number of tool changes and save on tool downloading time. Minimum machining time also helps in meeting the due dates. If the machining time is minimum less time is spent in the system. On the other hand minimum number of operations and minimum machining time will reduce the second criterion, namely the utilization of the system. Relative weights help to offset this negative effect by giving some importance to the two attributes. So we define a job to be "most suitable" or positive ideal if it has:

- \* closest due date
- \* minimum number of operations
- \* minimum machining time.

#### 7.3.4 NEGATIVE IDEAL SOLUTION

Negative ideal solution is defined as the least preferred solution. For the due date criterion this would mean selecting a job with

- \* later due date
- \* more operations

\* more machining time.

If the algorithm selected a job with the above characteristics, it would be impossible to meet the due dates, since the jobs with closer due dates would be ignored.

While it is undesirable to have an algorithm that will select jobs according the "negative ideal" characteristics, it is also impossible to select jobs with "positive characteristics only. Hence the TOPSIS algorithm calculates a separation measure and then ranks the jobs according to their proximity to either of the extreme situations. The algorithm was written and compiled in FORTRAN 77. A copy of the program is enclosed.

## CHAPTER VIII

### SIMULATION PROGRAMS

In this chapter we present the GPSSH simulation program for the flexible manufacturing system, and the Fortran subroutine for the scheduling algorithm.

#### 8.1 THE SIMULATION PROGRAM

Following is the simulation program in GPSSH that simulates the flexible manufacturing system. The program has been divided into five sections. These are the

- a. Planning section
- b. Machining section
- c. Scheduling section
- d. Control section
- e. Initialization section.

Details are as follows:

```
SIMULATE
RMULT      4999
REALLOCATE COM,140000
*****
* SCHEDULING AND OPTIMIZATION OF A FLEXIBLE MANUFACTURING
*                      SYSTEM
*                      BY
*                      BADRINATH THALLI K
*                      VERSION ORIGINAL
*****
*THE OBJECTIVE OF THIS THESIS IS TO SIMULATE A FLEXIBLE
```

\*MANUFACTURING SYSTEM AND TO SCHEDULE THE SYSTEM WITH  
\*MEETING DUE DATES AS THE OBJECTIVE. A SCHEDULING ALGORITHM  
\*DEVELOPED FOR THE DUE DATE OBJECTIVE WILL BE USED. THE  
\*FLEXIBLE MANUFACTURING SYSTEM CONSISTS OF A. 3 MACHINING  
\*CENTERS, B. A STORAGE AREA FOR THE PARTS C. AN AUTOMATED  
\*CONVEYOR, D. A LOAD AND UNLOAD AREA, E. 1 ROBOT. 25 PART  
\*TYPES ARE HANDLED BY THIS SYSTEM. THE MODEL DETAILS FOLLOW.  
\*\*\*\*\*

EXP FUNCTION RN1,C24

0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69/.6,.915/.7,1.2/.7  
5,1.38/.8,1.6/.0.84,1.83/.88,2.12/.9,2.3/.92,2.52/.94,2.81/.9  
5,2.99/.96,3.2/.97,3.5/0.98,3.9/.99,4.6/.995,5.3/.998,6.2/.9  
99,7/.9997,8

\*

TYPE FUNCTION RN1,D25

0.031,1/.066,2/.145,3/.155,4/.185,5/.252,6/.266,7/.297,8/.33  
4,9/.393,10/0.45,11/.49,12/.54,13/.62,14/.63,15/.68,16/.74,  
17/.816,18/.842,19/0.859,20/.878,21/.889,22/.907,23/.94,24/1  
,25

\*

\*\*\*\*\*  
\* PLANNING SECTION  
\*\*\*\*\*  
\*IN THIS SECTION OF THE PROGRAM SHOP ORDERS ARE RECEIVED  
\*FROM THE SALES DEPARTMENT AT AN EXPONENTIAL RATE. THESE  
\*ORDERS ARE ASSIGNED THEIR PART NUMBERS. NEXT THE NUMBER OF  
\*OPERATIONS REQD TO COMPLETE THE PART AND THE TOTAL  
\*MACHINING TIME REQD IS RECORDED. BASED ON THIS INFORMATION  
\*AND THE TOTAL MACHINING TIME AVAILABLE IN THE SYSTEM, A DUE  
\*DATE IS INDICATED FOR THE PART. IT IS ASSUMED THAT THIS DUE  
\*DATE IS ALWAYS ACCEPTABLE TO THE CUSTOMER AND THAT HE WON'T  
\*DEMAND THE PARTS EARLIER. ONCE THE DUE DATE IS FIXED THE  
\*ORDER THEN WAITS TO BE SCHEDULED IN THE SCHEDULING SECTION.  
\*\*\*\*\*

\*\*\*\*\*  
\*ATTRIBUTES MAKING UP THE REQUIRED DATABASE  
\*\*\*\*\*  
\* PH1 PARAMETER REPRESENTING PART TYPE  
\* PH2 PARAMETER REPRESENTING # OF OPERATIONS  
\* PH3 PARAMETER REPRESENTING TOTAL PROCESSING TIME  
\* PH4 PARAMETER REPRESENTING THE START DATE FOR ORDER  
\* PH5 PARAMETER REPRESENTING THE DUE DATE FOR THE ORDER  
\* PH6 PARAMETER REPRESENTING LAST LOCATION  
\* PH7 PARAMETER REPRESENTING PRESENT LOCATION  
\* PH8 PARAMETER REPRESENTING TOOL GROUP  
\* PH9 PARAMETER REPRESENTING MACHINE # IN USE

```

* PH10    PARAMETER REPRESENTING ORDER #
*****
*
* MX1      MATRIX CONTAINING TOOL GROUP AND OPERATION DETAILS
* MX2      MATRIX CONTAINING MACHINING TIME REQD FOR EACH OPN
* MX3      MATRIX WITH TOOL WEAR/USAGE, TOOL CHANGING TIME
* MX4      MATRIX FOR TRAVEL TIME POINT TO POINT.
* MX5      SET UP TIME FOR THE PARTS
* MX6      MATRIX THAT IS PASSED TO THE SCHEDULIONG CODE.
* MX7      MATRIX THAT RECORDS MACHINE USAGE TIME
*****
* XF1      SAVEVALUE WITH THE TOTAL SYSTEM CAPACITY IN HOURS
* XF2      SAVEVALUE WITH THE PRESENT AVAILABLE CAPACITY
*****
1      MATRIX      MX,25,28
2      MATRIX      MX,25,14
3      MATRIX      MX,4,5
4      MATRIX      MX,7,7
5      MATRIX      ML,800,6
6      MATRIX      ML,800,4
7      MATRIX      ML,3,8
8      MATRIX      MX,800,5

*****
*          PLANNING SECTION
*****
*IN THIS SECTION THE ORDERS ARE RECEIVED FROM THE SALES AND
ALL THE PLANNING FUNCTIONS ARE CARRIED OUT. THE TOTAL
MACHINING TIME, DUE DATE, AND # OF OPERATIONS ARE RECORDED.
THE ORDER THEN WAITS TO BE DISPATCHED TO THE MACHINING AREA.
*****



GENERATE 20,FN$EXP,,,12PH,7PF,3PL GENERATE THE
          ORDERS FOR THE FMS
TEST G     XL4,0,REJ      TEST WHETHER THE SYS
           IS FULL
SAVEVALUE  3+,1,XF       RECORD THE ORDER
ASSIGN    10,XF3,PH      ASSIGN THE ORDER NOS
ASSIGN    1,FN$TYPE,PH   ASSIGN THE PART TYPES

ASSIGN    2, MX1(PH1,14),PH .  ASSIGN THE # OF
                           OPERATIONS
ASSIGN    3, MX2(PH1,14),PH .  ASSIGN THE TOTAL
                           PROC. TIME
ASSIGN    7,C1,PF         ASSIGN THE START DATE
ASSIGN    1,V1,PL         ASSIGN THE DUE DATE
ASSIGN    2,V2,PL
SAVEVALUE 4-, (PH3+6.00+1.5*PH2),XL TOTAL TIME AVL
SAVEVALUE 1,V6,XL        CHECK FOR DUE DATE

```

TEST LE	PL2,(XL1+0.8),*+3	LESS THAN DAY 1 CHECK FOR ROUND OFF
ASSIGN	2,XL1,PL	ASSIGN ROUNDED DATE
TRANSFER	,*+2	
ASSIGN	2,(XL1+1),PL	
		ASSIGN FOR NEXT DATE IF THE DUE DATE WORKS OUT TO MORE THAN THE 6TH HOUR OF SHIFT.
ASSIGN	5,PL2,PH	
MSAVEVALUE	5-6,PH10,1,PH5,ML	
MSAVEVALUE	.5-6,PH10,2,PH2,ML	INPUT DUE DATE INTO MATRIX
MSAVEVALUE	5-6,PH10,3,PH3,ML	INPUT # OF OPERATIONS INTO MATRIX
MSAVEVALUE	5-6,PH10,4,PH10,ML	INPUT TOTAL PROC.
MSAVEVALUE	5,PH10,6,PF7,ML	TIME
SAVEVALUE	9+,1,XF	INPUT THE ORDER #
ENTER	WIP	RECORD THE ENTRY OF THE ORDER
TABULATE	2	RECORD AS WIP TABULATE WIP
TEST G	XF3,4,MACH	
LINK	1,FIFO	
MACH	MSAVEVALUE 6,PH10,1-3,0,ML	IS THE MACHINE YET TO BE LOADED GET ON TO THE USER CHAIN
TEST E	BV1,1	CANCEL THIS ORDER AS DISPATCHED
QUEUE	3	ANY MACHINES AVAILABLE?
ENTER	MILLING	QUEUE FOR MACHINES ENTER THE MACHINING AREA. THIS IS USED FOR THE DIFF JOB POLICIES
DEPART	3	LEAVE THE QUEUE
MARK	1PF	START RECORDING TRAVEL TIME
ENTER	LOAD	ENTER THE LOAD AREA
ASSIGN	6,4,PH	ASSIGN THIS AS PREV LOCATION
ASSIGN	7,5,PH	THIS IS THE PRESENT LOCATION
ENTER	PH7	RECORD ENTRY INTO LOAD AREA
ENTER	CONVEYOR	ENTER THE CONVEYOR
ADVANCE	MX4(PH6,PH7)	TRAVEL TIME FOR THE PART
TABULATE	4	TABULATE TRAVEL TIME

LEAVE CONVEYOR  
 MSAVEVALUE 7+, 1, 4, MP1PF, ML  
 ASSIGN 6, PH7, PH  
 LEAVE THE CONVEYOR  
 RECORD TRAVEL TIME IN  
 MATRIX  
 THIS BECOMES THE PREV  
 LOCATION

---

\* MACHINING SECTION

---

\*IN THIS SECTION THE DISPATCHED ORDER SELLECTS A MACHINE AND  
 \*GETS READY FOR MACHINING. THE ORDER HAS TO SHARE THE ROBOTS  
 \*WITH ALL THE OTHER ORDERS IN THE SYSTEM. TIME MAY BE  
 \*CONSUMED FOR TOOL CHANGING, AND TOOL DOWNLOADING.

---

CONT	ASSIGN	8, MX1(PH1, PH2), PH	ASSIGN THE TOOL GROUP FOR THE ORDER
	TEST G	MX1(PH1, PH2+14), 0, GO	DOES THE PART NEED FIXTURING
	MARK	2PF	START RECORDING WAITING TIME
	QUEUE	1	ENTER QUEUE FOR ROBOT
	ENTER	10	ENTER THE ROBOT
	DEPART	1	LEAVE THE QUEUE
	TABULATE	5	TABULATE QUEUE TIME
	MSAVEVALUE	7+, 1, 5, MP2PF, ML	RECORD THE QUEUE WAITING TIME
	MARK	3PF	START RECORDING FIXTURING TIME
	ADVANCE	MX1(PH1, PH2+14)	TIME TO TURN PART OVER
	LEAVE	10	LEAVE THE ROBOT
	TABULATE	6	TABULATE FIXTURING TIME
	MSAVEVALUE	7+, 1, 6, MP3PF, ML	RECORD FIXTURING TIME
GO	TEST E	BV1, 1	ANY MACHINES AVAILABLE?
	SELECT NU	9PH, 1, 3	SELECT THE MACHINE
	ENTER	CONVEYOR	ENTER THE CONVEYOR
	ADVANCE	2	TRAVEL TIME TO MACHINE
	SEIZE	PH9	SEIZE THE MACHINE
	LEAVE	CONVEYOR	LEAVE THE CONVEYOR
	TEST GE	MX3(PH8, PH9), MX3(PH8, 4), AHEAD	TOOLS NEED CHANGE?
	MARK	4PF	START RECORDING TOOL CHANGE TIME
	ADVANCE	MX3(PH8, 5)	CHANGE TOOLS
	MSAVEVALUE	3, PH8, PH9, 0, MX	RESET THE TOOL GRP TIME FOR THE M/C
	TABULATE	7	TABULATE TOOL CHANGE TIME

	MSAVEVALUE	7+, 1, 7, MP4PF, ML	RECORD THE TOOL CHANGE TIME
AHEAD	MARK	5PF	START RECORDING
	ADVANCE	XH*(PH8+4)	DOWNLOADING TIME
	TABULATE	8	TOOL DOWNLOADING IS ON
	MSAVEVALUE	7+, 1, 8, MP5PF, ML	TABULATE TOOL DOWNLOADING TIME
	MARK		RECORD TOOL DOWN LOADING TIME
	ADVANCE	MX2(PH1, PH2)	START RECORDING THE MACHINING TIME
	TABULATE	9	MACHINE THE PART FOR THE OPERATION
	MSAVEVALUE	7+, 1, PH9, M1, ML	TABULATE MACHINING TIME
	MSAVEVALUE	3+, PH8, PH9, MX2(PH1, PH2), MX	RECORD THE MACHINING TIME
	RELEASE	ADD TO TOOL WEAR TIME	WEAR TIME
	GATE SNF	MILLING, TOP	RELEASE THE MACHINE ENOUGH PARTS IN THE MACHINE
	SPLIT	1, SCHED	SEND ORDERS FOR FURTHER DISP.
	PRIORITY	1	PRIORITIZE THIS ORDER
TOP	LOOP	2PH, CONT	LOOP BACK FOR THE NEXT OPERATION
	MSAVEVALUE	5, PH10, 5, V3, ML	RECORD FINISH DATE IN DATABASE
	TABULATE	11	TABULATE FINISH DATE
	TEST G	ML5(PH10, 5), 0, *+4	IS THE JOB ON TIME
	ENTER	LATE	JOB IS LATE
	MSAVEVALUE	7+, 3, 1, 1, ML	RECORD THE LATENESS
	TABULATE	10	TABULATE LATENESS
	ENTER	CONVEYOR	ENTER THE CONVEYOR
	ENTER	UNLOAD	ENTER THE UNLOAD AREA
	ENTER	PROD	RECORD AS A PRODUCTION UNIT
	TEST G	V3, 0, *+2	IS THE LATENESS POSITIVE
	MSAVEVALUE	7+, 3, 2, V3, ML	RECORD TARDINESS
	TABULATE	1	TABULATE PRODUCTION
	ASSIGN	7, 6, PH	THIS IS THE PRESENT LOCATION
	MARK	6PF	START RECORDING
	ADVANCE	MX4(PH6, PH7)	TRAVEL TIME
	TABULATE	4	TRAVEL TIME

LEAVE	CONVEYOR	LEAVE THE CONVEYOR
LEAVE	MILLING	LEAVE MACHINING AREA
MSAVEVALUE	7+, 1, 4, MP6PF, ML	RECORD TRAVEL TIME
MSAVEVALUE	7+, 2, 4, (MP6PF/AC1), MLCALCULATE % TRAVEL	TIME

\*\*\*\*\*

\* SCHEDULING SECTION

\*\*\*\*\*

\*THIS SECTION TAKES CARE OF THE JOB OF THE SCHEDULER.

\*WHENEVER A MACHINE GETS FREE AFTER COMPLETING AN ORDER, THE \*SCHEDULER IS TRIGGERED ON. THIS INVOKES THE HELP BLOCK.

\*THIS HELP BLOCK ACCESSES THE FORTRAN SUBROUTINE THAT \*DIRECTS THE SCHEDULING. THE SCHEDULED ORDER IS UNLINKED \*FROM THE USER CHAIN AND THEN SENT FOR MACHINING.

\*\*\*\*\*

SCHED GATE SNF	MILLING, TERM	CHECK WHETHER THE MACHINES ARE FULL
----------------	---------------	-------------------------------------

	TEST G	CH1,0,TERM	ANY PARTS YET TO BE DISPATCHED
	TEST E	CH1,1,HELL	IS THERE MORE THAN ONE
	UNLINK	1,MACH,1	SEND IT TO MACHINING AREA
	TRANSFER	, TERM	
HELL	QUEUE	2	QUEUE FOR SCHEDULER
	GATE NU	BOSS	IS SCHEDULER IN USE
	SEIZE	BOSS	SEIZE THE SCHEDULER
	DEPART	2	LEAVE THE QUEUE
	HELP C	TEST, 6	START THE SCHEDULING ALGORITHM
	UNLINK	1,MACH,1,10PH,XH2	DISPATCH THIS ORDER
TERM	RELEASE	BOSS	RELEASE THE SCHEDULER
TERMINATE	TERMINATE		
REJ	ENTER	REJECT	SORRY CAN'T ACCEPT YOUR ORDER. THERE IS NOT ENOUGH MACHINING TIME
	TABULATE	3	TABULATE REJECTS
	TERMINATE		

\*\*\*\*\*

\*\*\*\*\*

\* CONTROL SECTION

\*\*\*\*\*

\*THIS IS THE CONTROL SECTION OF THE ENTIRE SYSTEM. THE \*ENTIRE FUNCTION OF THE FLEXIBLE MANUFACTURING SYSTEM IS \*CONTROLLED IN THIS SECTION. THE NUMBER OF HOURS THE SYSTEM

OPERATES, AND INITIALIZATION AND STUDYING THE FEED BACK ARE  
\*SOME OF THE FUNCTIONS.

```
*****
GENERATE    ,,,1          GENERATE THE
CONTROLLER
A   ADVANCE    1200        WAIT FOR THE DAY TO
BE OVER
SAVEVALUE   8+,1,XL       TODAY'S DATE
LEAVE       PROD,S$PROD  CLEAR THE DAY'S
PRODUCTION
LEAVE       WIP,S$WIP     CLEAR THE DAY'S WIP
LEAVE       REJECT,S$REJECT  CLEAR THE DAY'S REJECT
LEAVE       LATE,S$LATE    CLEAR THE LATE JOBS
ASSIGN      1,600,PH
ADD   TEST G    ML5(PH1,5),0,BACK  CHECK FOR LATE JOB
MSAVEVALUE  8,PH1,1,ML5(PH1,4),MX  RECORD STATISTICS OF
MSAVEVALUE  8,PH1,2,ML5(PH1,2),MX  LATE JOBS
MSAVEVALUE  8,PH1,3,ML5(PH1,3),MX
MSAVEVALUE  8,PH1,4,ML5(PH1,5),MX
MSAVEVALUE  7+,3,6,ML6(PH1,3),ML
BACK   LOOP      1PH,ADD      GO BACK FOR THE NEXT
RECORD
TEST G    ML7(3,1),0,*+2  ANY JOBS COMPLETED
MSAVEVALUE 7,3,3,SC$PROD,ML  RECORD JOBS PRODUCED
MSAVEVALUE 7,3,4,V4,ML     CALCULATE MEAN LATENESS
MSAVEVALUE 7,3,5,(TC2-TC1),ML # OF REJECTS
ASSIGN      3,8,PH
AA    MSAVEVALUE 7,2,PH3,(ML7(1,PH3)/AC1),ML % MACHINE UTILIZATION
LOOP      3PH,AA
SPLIT      1,A           MAKE A COPY FOR
TOMORROW
TERMINATE   1
1    TABLE      S$PROD,0,10,100
2    TABLE      S$WIP,0,10,100
3    TABLE      S$REJECT,0,10,100
4    TABLE      MP1PF,100,10,10  DETAILS OF THE
VARIOUS TABLES
5    TABLE      MP2PF,100,10,10
6    TABLE      MP3PF,100,10,10
7    TABLE      MP4PF,100,10,10
8    TABLE      MP5PF,100,10,10
9    TABLE      M1,100,10,10
10   TABLE      S$LATE,0,1,10
11   TABLE      V3,-1,1,12
12   QTABLE    4,0,10,20
1    EVARIABLE  FNU1+FNU2+FNU3  CHECK FOR THE FREE
MACHINING CENTER
1    FVARIABLE  (XL3-XL4)/(3600)  FIX THE START DATE
2    FVARIABLE  (PL1+((PH3+6.00+1.5*PH2)/(3600)))+1.0  FIX
THE DUE DATE
```

```

3   FVARIABLE  XL8-PH5
4   FVARIABLE  ML7(3,2)/TC1          FORMULA FOR MEAN
5   VARIABLE    PL3/1               TARDINESS
6   VARIABLE    PL2/1

*****
*           INITIALIZATION SECTION
*****
*IN THIS THE INITIALIZATION OF THE MATRICES IS CARRIED OUT.
*MATRIX 1 AND 2 ARE INITIALIZED IN THE ORDER OF PART
*FAMILIES. FOR SAVEVALUE 1 THE INITIAL VALUE HAS BEEN
*CALCULATED USING THE FORMULA W*S*H(1-TC).W:# OF WORKCENTERS
*H: # OF HOURS AVAILABLE/DAY, S: # OF DAYS, TC:PERCENT TIME
*FOR TOOL CHANGE.
*****
INITIAL  MX1(1-6,4-7),1/MX1(1-6,3),3/MX1(1-6,1-2),4
INITIAL  MX1(1-6,14),7
INITIAL  MX1(7-10,5-8),1/MX1(7-10,3-4),3/MX1(7-
          10,1-2),4
INITIAL  MX1(7-10,14),8
INITIAL  MX1(11-16,4-7),1/MX1(11-16,3),3/MX1(11-
          16,1-2),4
INITIAL  MX1(11-16,14),7
INITIAL  MX1(17-19,2-3),2/MX1(17-19,1),3/MX1(17-
          19,14),3
INITIAL  MX1(20-21,1-4),2/MX1(20-21,14),4
INITIAL  MX1(22-25,2-13),2/MX1(22-25,1),3/MX1(22-
          25,14),13
*****
INITIAL  MX2(1,4-7),12/MX2(1,3),66.5/MX2(1,2),5/MX2
          (1,1),2
INITIAL  MX2(2,4-7),15/MX2(2,3),66.5/MX2(2,2),5/MX2
          (2,1),2
INITIAL  MX2(3,4-7),14/MX2(3,3),46/MX2(3,2),5/MX2(3
          ,1),2
INITIAL  MX2(4,4-7),18/MX2(4,3),36/MX2(4,2),5/MX2(
          4,1),2
INITIAL  MX2(5,4-7),18/MX2(5,3),87/MX2(5,2),5/MX2(5
          ,1),2
.
INITIAL  MX2(6,4-7),14/MX2(6,3),66/MX2(6,2),5/MX2(6
          ,1),2
INITIAL  MX2(7,5-8),18/MX2(7,4),56/MX2(7,2-3),5/MX2
          (7,1),2
INITIAL  MX2(8,5-8),16/MX2(8,4),44/MX2(8,2-3),5/MX2
          (8,1),2
INITIAL  MX2(9,5-8),17/MX2(9,4),46/MX2(9,2-3),5/MX2
          (9,1),2

```

INITIAL	$MX2(10,5-8), 14/MX2(10,4), 32/MX2(10,2-3), 5/$
	$MX2(10,1), 2$
INITIAL	$MX2(11,4-7), 12/MX2(11,3), 48/MX2(11,2), 8/MX$
	$2(11,1), 3$
INITIAL	$MX2(12,4-7), 9/MX2(12,3), 36/MX2(12,2), 8/MX$
	$2(12,1), 3$
INITIAL	$MX2(13,4-7), 16/MX2(13,3), 42/MX2(13,2), 6/MX$
	$2(13,1), 3$
INITIAL	$MX2(14,4-7), 13/MX2(14,3), 35/MX2(14,2), 8/MX$
	$2(14,1), 3$
INITIAL	$MX2(15,4-7), 16/MX2(15,3), 42/MX2(15,2), 6/MX$
	$2(15,1), 3$
INITIAL	$MX2(16,4-7), 14/MX2(16,3), 35/MX2(16,2), 8/MX$
	$2(16,1), 3$
INITIAL	$MX2(17,2-3), 55/MX2(17,1), 130$
INITIAL	$MX2(18,2-3), 70/MX2(18,1), 140$
INITIAL	$MX2(19,2-3), 80/MX2(19,1), 150$
INITIAL	$MX2(20,1-4), 38$
INITIAL	$MX2(21,1-4), 45$
INITIAL	$MX2(22,2-13), 10/MX2(22,1), 30$
INITIAL	$MX2(23,2-5), 10/MX2(23,6-9), 12/MX2(23,10-13)$
	$, 10$
INITIAL	$MX2(23,1), 30$
INITIAL	$MX2(24,2-5), 12/MX2(24,6-9), 14/MX2(24,10-13)$
	$, 12$
INITIAL	$MX2(24,1), 25$
INITIAL	$MX2(25,2-5), 12/MX2(25,6-9), 17/MX2(25,10-13)$
	$, 16$
INITIAL	$MX2(25,1), 20$
INITIAL	$MX2(1,14), 122/MX2(2,14), 134/MX2(3,14), 109$
INITIAL	$MX2(4,14), 115/MX2(5,14), 166/MX2(6,14), 129$
INITIAL	$MX2(7,14), 140/MX2(8,14), 120/MX2(9,14), 120$
INITIAL	$MX2(10,14), 100/MX2(11,14), 107/MX2(12,14), 8$
	$1$
INITIAL	$MX2(13,14), 115/MX2(14,14), 98/MX2(15,14), 115$
INITIAL	$MX2(16,14), 102/MX2(17,14), 240/MX2(18,14), 2$
	$80$
INITIAL	$MX2(19,14), 310/MX2(20,14), 152/MX2(21,14), 1$
	$80$
INITIAL	$MX2(22,14), 150/MX2(23,14), 158/MX2(24,14), 1$
	$77$
INITIAL	$MX2(25,14), 200$
*****	*****
INITIAL	$MX1(1-6,18-21), 2$
INITIAL	$MX1(7-10,19-22), 2$
INITIAL	$MX1(11-16,18-21), 3$
INITIAL	$MX1(17-19,15), 5$
INITIAL	$MX1(17-19,16-17), 4$

```
INITIAL    MX1(22-25,16-27),2
*****
INITIAL    MX3(1,4),400/MX3(1,5),16
INITIAL    MX3(2,4),400/MX3(2,5),16
INITIAL    MX3(3,4),700/MX3(3,5),20
INITIAL    MX3(4,4),640/MX3(4,5),16
*****
INITIAL    MX4(4,5),5/MX4(5,6),3/MX4(7,5),3/MX4(5,7),
            3
INITIAL    XL3,36000
INITIAL    XL4,36000
INITIAL    XH5,1
INITIAL    XH6,2
INITIAL    XH7,1
INITIAL    XH8,2
INITIAL    XL8,1
STORAGE    S$MILLING,4
STORAGE    S$CONVEYOR,1
STORAGE    S10,1
INITIAL    LS1
INITIAL    XL3,36000
INITIAL    XL4,36000
INITIAL    XL8,1
START      10
RESET      TB1,TB2,TB11
INITIAL    XL3,36000
INITIAL    XL4,36000
INITIAL    XL8,1
START      10
END.
```

\*\*\*\*\*

## 8.2 FORTRAN SUBROUTINE

The fortran sub-routine which simulated the TOPSIS algorithm, is shown below.

```
SUBROUTINE TEST
1 (ARGS,FSV,HSV,FAC,STO,STOL,QUE,QUEL,LOG,TAB,TABL,
2 CHAH,CHA,CHAL,FMS,FMSPTS,HMS,HMSPTS,LSV,
3 LMS,LMSPTS,BSV,BMS,BMSPTS)
CC
      REAL*8 STOL(2),QUEL(2),TABL(2),CHAL(2)
      INTEGER*4 ARGS(6),FSV(2),FAC(2),STO(2),QUE(2),TAB(2)
      INTEGER*4 CHA(2),FMS(2),FMSPTS(2),HMS(2)
      INTEGER*4 LMS(2),BMS(2)
      REAL*4 LMSPTS(2),LSV(2)
      INTEGER*2 HSV(2),CHAH(2),HMSPTS(2)
      LOGICAL*1 LOG(2),BSV(2),BMSPTS(2)
CC
      DIMENSION X(800,4),SPOS(4),WT(4),BIG(4),SMALL(4),
      *CLOS(800),SPIS(800),SNIS(800),BEST(800),SIS(800),
      *SUM(3),Y(800,3),CIS(800)
C*****
CTHIS IS THE START OF THE SCHEDULING ALGORITHM
C*****
CALL FTINIT
WT(1)=0.60
WT(2)=0.20
WT(3)=0.20
WT(4)=0.0
C
CALL FTINIT
C*****
CTHIS SECTION DETERMINES THE # OF ROWS,COLS,AND ADDRESS OF
C(1,1)
C*****
IADDR=LMS(3*(ARGS(1)-1)+1)
NROWS=LMS(3*(ARGS(1)-1)+2)
NCOLS=LMS(3*(ARGS(1)-1)+3)
C
NCOLS = COLMS-1
C*****
CTHIS SECTION COPIES DOWN THE MATRIX PASSED
C*****
DO 150 J = 1,NCOLS
DO 150 I = 1,NROWS
```

```

*****
C THIS FORMULA IS TO ACCESS THE INDIVIDUAL CELL ELEMENT
*****
150 X(I,J) = LMSPTS(IADDR/4+NCOLS*(I-1)+J-1)
    DO 10 J = 1,NCOLS
        SUM(J) = 0.0
        DO 10 I = 1,NROWS
            IF (X(I,J).GT.0)SUM(J) = SUM(J)+X(I,J)**2
10    CONTINUE
*****
C NORMALIZING AND WEIGHTING THE MATRIX
*****
DO 20 J = 1,NCOLS
DO 20 I = 1,NROWS
IF ((X(I,J).GT.0).OR.(SUM(J).GT.0))
*X(I,J)=(X(I,J)/SQRT(SUM(J)))
20    CONTINUE
C WEIGHTING THE MATRIX
DO 30 J = 1,NCOLS
DO 30 I = 1,NROWS
IF (X(I,J).GT.0)X(I,J) = (X(I,J)*WT(J))
30    CONTINUE
*****
C THIS SECTION DETERMINES NEGATIVE IDEAL SOLUTION
*****
DO 40 J = 1,NCOLS
BIG(J) = X(1,J)
DO 40 I = 1,NROWS
40    IF((X(I,J).GT.BIG(J)).AND.(X(I,J).NE.0)) BIG(J)=X(I,J)
*****
CC THIS SECTION DETERMINES POSITIVE IDEAL SOLUTION
*****
DO 50 J = 1,NCOLS
SMALL(J)=500000
DO 50 I = 1,NROWS
50    IF ((X(I,J).LT.SMALL(J)).AND.(X(I,J).NE.0))
        SMALL(J)= X(I,J)
*****
CC THIS SECTION DETERMINES THE SEPARATION MEASURE
*****
DO 60 I = 1,NROWS
SIS(I) = 0.0
DO 120 J = 1,NCOLS
IF (X(I,J).GT.0)SIS(I)=SIS(I)+(X(I,J)-BIG(J))**2
120    CONTINUE
SPIS(I)=SQRT(SIS(I))
60    CONTINUE
CC SEPARATION MEASURES NIS
DO 70 I = 1,NROWS
SNIS(I)=0.0

```

```

DO 130 J = 1,NCOLS
  IF (X(I,J).GT.0)SNIS(I)=SNIS(I)+(X(I,J)-SMALL(J))**2
130  CONTINUE
      CIS(I)=SQRT(SNIS(I))
70   CONTINUE
C*****
CC   THIS SECTION MEASURES RELATIVE CLOSENESS
C*****
      DO 100 I = 1,NROWS
100  IF((CIS(I).GT.0).OR.(SPIS(I).GT.0))
      *CLOS(I)=SPIS(I)/(SPIS(I)+CIS(I))
C*****
CC   THIS SECTION FINDS THE BEST ORDER TO BE DISPATCHED
C*****
      BEST(1)=0.0
      DO 110 I = 1,NROWS
      IF(CLOS(I).LT.BEST(1)) GO TO 110
      BEST(1)=CLOS(I)
      K=I
      CLOS(I)=0.0
110  CONTINUE
      J=4
C*****
C HELPC BLOCK ALLOWS GPSS ENTITIES TO BE ACCESSED. THIS
C PROPERTY IS USED HERE TO DISPATCH THE ORDER.  BESTI ABOVE
C GIVES THE VALUE AND FOR THAT 'I' THE ORDER # IS DETERMINED
C USING THE FORMULA SHOWN BELOW
C*****
      HSV(2)=LMSPTS(IADDR/4+NCOLS*(K-1)+J-1)
C      HSV(2)=K
C      K=0.0
      WRITE(6,*)"THIS IS ORDER DISPATCHED",HSV(2)
      RETURN
      END

```

## CHAPTER IX

### ANALYSIS OF RESULTS

The previous chapters dealt with the research, design, development, simulation of the flexible manufacturing system and the scheduling algorithm for the system. In this chapter we concern ourselves with the analysis of the system performance and the benefits of our scheduling algorithm. The analysis of the system performance will be based on our objectives namely:

- \* Due dates
- \* Machine utilization

#### 9.1 PARAMETERS INFLUENCING SYSTEM PERFORMANCE

The performance of the flexible manufacturing system was influenced and affected by three variable parameters, namely

1. Loading policy,
2. Attributes considered and their importance in the scheduling algorithm,
3. Scheduling period.

##### 9.1.1 Loading Policy

By loading policy we refer to the number of jobs that could

be released for machining to the machining area. Two different policies were tried out and their results analyzed.

In loading policy 1 the rule was "as many jobs as there are machines". We refer to this as the 3 job policy. According to this policy, there would not be more than three jobs released for machining. Since there were only three machining centers it was logical that at any time there would be three jobs in the machining area. The machines would remain idle when the jobs were being refixtured, or reoriented. Figure 4 indicates the break up of time when this policy was followed. An analysis of the system performance is presented later.

Since the system being scheduled was a flexible manufacturing system, a new policy was devised which would take advantage of the flexibility in the system. The loading policy 2 allowed 4 jobs at a time to be released for machining. This is referred to as the 4 job policy. This meant that there could be 4 jobs in the machining area; whenever a part was being refixtured the additional job would occupy the free machine. This policy essentially ensured that there was always an extra job waiting to take over a free machine. The policy allowed parts which were partially processed to have a priority in utilizing the

machines. Interesting results were derived. Figure 5 indicates the break up of time, for a machine when this policy was pursued.

#### **9.1.2 IMPORTANCE OF JOB ATTRIBUTES**

As mentioned earlier in Chapter VII the three attributes of the jobs, considered while scheduling the jobs included:

- \* due date of the job
- \* the number of operations required to complete the job
- \* the total machining time required to complete the job.

As explained in Chapter VII relative weights were assigned to these attributes in the TOPSIS algorithm. The weights indicated the relative importance of each of the attributes. Since due date was the most important criteria in scheduling the system, we started with a higher weight for the due date attribute. Initially the weights considered were 0.6 for due dates, 0.2 for both number of operations and machining time required. Thus while the due date attribute is most important, the other two factors are not ignored. These weights on the attributes were further modified to study the system performance. The various weight combinations studied are indicated in Section 9.1.4.

### **9.1.3 SCHEDULING PERIOD**

It was decided to study the performance of the system over prolonged scheduling periods of time. For this reason two scheduling periods were used. Refer section 9.1.4.

### **9.1.4 EXPERIMENT CONDITIONS**

The following were the conditions under which the performance of the flexible manufacturing system was studied:

- Loading Policy(NUM): a. 3 jobs in the system (3 job policy)  
b. 4 jobs in the system (4 job policy)

Weights considered(WT):

Code used	Ref code	due date	# of operations	machining time
202060	a	0.20	0.20	0.60
206020	b	0.20	0.60	0.20
403030	c	0.40	0.30	0.30
601030	d	0.60	0.10	0.30
602020	e	0.60	0.20	0.20
603010	f	0.60	0.30	0.10
801010	g	0.80	0.10	0.10

- Scheduling period(DAYS): a. 10 days  
b. 20 days

Performance parameters:

Mean Lateness (ML)

Machine Utilization (UTL)

## **9.2 ANALYSIS OF DUE DATE PERFORMANCE**

Due date performance was measured in terms of mean tardiness. For every job produced the lateness was recorded. The lateness of jobs with a positive lateness (tardiness) was calculated, and their mean value used as a measure of due date performance. The total production during the scheduling period was used in the calculation of mean lateness. Smaller mean lateness meant that more jobs were being completed on time. This positive lateness is termed as tardiness in the literature.

### **9.2.1 STATISTICAL ANALYSIS**

A randomized complete block design, with the scheduling period (days) as the blocking factor was used. An analysis of variance for the mean lateness was conducted. Results are as follows:

Table 1

ANOVA Table for Mean Lateness

Dependent Variable: ML (mean lateness)

Source	df	sum of squares		
Model	14	9.747		
Error	125	1.697		
Total	139	11.444		
Source		Anova S S	F value	PR>F
WT	6	7.934	97.40	0.0001
NUM	1	1.273	93.75	0.0001
DAYS	1	0.016	1.23	0.2693
WT*NUM	6	0.522	6.42	0.0001

The Anova table for the Mean lateness indicates the following:

1. There is a statistically significant difference among the different weight combinations used.
2. There is a statistically significant difference between the two loading policies (NUM) applied.
3. The scheduling period (DAYS) did not make a statistically significant difference. This justified our using the DAYS as a blocking factor.

The means least significant difference (LSD) procedure of the data collected indicated the following:

Table 2

Least Significant Difference of Weight Combinations  
Weights (WT)

Grouping	Mean (days)	N	WT
A	1.12250	20	206020
B	0.89050	20	202060
C	0.54900	20	603010
C	0.54250	20	403030
C	0.52150	20	801010
D	0.45400	20	601030
D	0.45250	20	602020

We conclude the following from the above:

- a. With increasing importance on the due date the mean lateness decreases.
- b. Beyond a certain point the due date factor is not significant. For example the difference between using (0.6) and (0.8) weights for due dates is not significant.
- c. The weight combination of 602020 (0.6, 0.2, 0.2) gives rise to the best performance for this system. The mean lateness was the least in this case with a value of 0.452 days.

#### Loading Policy (NUM)

- a. There was a statistically significant difference between the two loading policies, of either having 3 or 4 jobs.
- b. The 4 job policy gave a better performance. The mean lateness in this case was 0.55214 days compared to

0.74286 days with the 3 job policy.

#### **9.2.2 GRAPHICAL ANALYSIS**

- a. For a given loading policy (3 or 4 jobs), there is an increase in mean lateness between the two scheduling periods considered. This is true for weight combinations with more than 0.2 importance for due dates. Refer Figure 1.
- b. The 4 job policy gives a lower mean lateness compared to the 3 job policy. Refer Figure 2. This is true for both the scheduling periods considered.
- c. Figure 1 also indicates that with increasing importance to the due date factor, the mean lateness decreases considerably. An importance factor of 0.6 for due dates gives the best performance in this simulation study.

#### **9.3 MACHINE UTILIZATION ANALYSIS**

Machine utilization was measured as the fraction of time period when the machine was actually used for cutting. This time was recorded in terms of time units as well as a percentage of the total run time. The time spent in non-machining activities included tool change time, tool downloading time. Traveling time to the machining area and any

other time delay due to functional problems are added to the idle time component. The utilization of each of the machining centers was recorded separately and analyzed.

#### 9.3.1 GRAPHICAL ANALYSIS

The following were the results obtained on the utilization of machines:

- a. There was a significant difference in the utilization of machines between the two loading policies. The 4 job policy gave a higher utilization (average: 89%) than the 3 job policy (average: 80%); Figure 3 also indicates this clearly. This was true for all the weight combinations considered. The presence of an additional job waiting to occupy an idle machine helps to reduce the idle time. This results in an increase in the utilization of the machines. Figures 4, 5, and 6 give the details of the total machining and non-machining time. These figures show that with 4 jobs in the system the idle time is reduced to 623 minutes from the 4415 minutes with 3 jobs in the system. At the same time the tool change time and tool downloading time increases, because of the additional jobs processed.
- b. For a given loading policy the machine utilization was not affected significantly by the different weight

- combinations. This is shown in Figure 7.
- c. The scheduling period length did not have a significant effect on the machine utilization for a given loading policy, as shown in Figure 8. This was true for all the three machining centers.
  - d. All the three machines were loaded uniformly under any of the given conditions. Refer to Figure 7.

#### **9.4 VALIDATION OF RESULTS**

The uniform utilization of the machines under all the different conditions suggested that there were more parts in the system than could be completed within the available machining time. This forced us to examine the calculation of the available machining capacity. We noticed that even though the machining centers were idle when tools were being changed or downloaded, the time lost was not taken into account. This resulted in more jobs being accepted for machining, within a scheduling period, than could be accommodated.

In order to study the effect of the time component due to tool changing and tool downloading, we calculated the average time spent on tool changing and downloading for each part. The average time spent on tool changing was about 7.73 minutes and that on tool downloading was 1.5 minutes

for every part. These two time components were added to the machining time to give the total time required to completely machine the part. By varying these time components we were able to simulate three different conditions of load on the system. This was accomplished as follows:

- a. By increasing the tool changing time to 8.00 minutes for every part, we accepted fewer parts for a given scheduling period. This meant that the system was being underloaded.
- b. By maintaining the tool changing time at 7.73 minutes we were keeping the system loaded to its right capacity. We term this condition as the "just loaded condition."
- c. By decreasing the tool changing time to 6.00 minutes we were once again accepting more than acceptable number of parts into the system for a scheduling period. This meant that we were once again overloading the system.

The analysis of the above three conditions gave us the following results:

- a. There was no significant difference in using either of the three conditions, as far as due date performance was concerned. However, Figure 9 shows that the mean lateness was the least when the system was overloaded. Analysis of variance (ANOVA) results for the mean lateness are as follows:

Note: Cond refers to the three conditions, namely under loaded, just loaded, and overloaded.

Table 3  
Anova Table for Different Load Conditions

Dependent variable: ML(mean lateness)

Source	df	Anova SS	F value	PR>F
Cond	2	0.00337638	3.44	0.0609
Days	1	0.00075014	1.53	0.2366

- b. Machine utilization was again not affected significantly under any of the three load conditions. Figure 10 shows the utilization under the three conditions. The system although termed underloaded has the right number of parts for the scheduling period. When it is overloaded it is able to produce an extra part or two, giving a better due date performance.
- c. The scheduling period did not make a statistically significant difference on the due date performance under any of three load conditions. However, there was a small accumulation of mean lateness with the 20 day scheduling period. This is shown by the analysis of variance (ANOVA) results:

Table 4

## ANOVA Table for Different Scheduling periods

Dependent variable: ML (Mean Lateness)

source	df	Anova SS	F value	PR>F
Days	2	0.00045921	0.39	0.6928.

**9.5 INCREASING THE NUMBER OF JOBS TO MORE THAN FOUR**

Since the 4-job policy gave a better due date performance and a higher machine utilization, we studied the effect of having 5, 6, and 7 jobs in the system. Our study indicated the following:

- a. The mean lateness of jobs did not change significantly by increasing the number of jobs in the machining area up to seven. As far as the system was concerned it was just one extra job. We also felt that with more than one job in the machining area there was a possibility of confusion in the absence of clear priority rules.
- b. The machine utilization was not affected by increasing the number of jobs in the system up to seven.
- c. The reader may refer Figures 4, 5, and 6 for the idle time for the three loading policies discussed above.

**9.6 CAPACITY CONSTRAINTS OF THE MATERIAL HANDLING SYSTEM**

At the end of our analysis of results we felt that our assumption on the conveyor capacity was not realistic.

We felt that the robots might be a bottleneck in the system.  
Accordingly we studied and observed the following:

- \* Conveyer with a capacity to carry 1 or 2 or more parts
- \* Presence of 1 or 2 or more robots in the system.

WT: 602020    NUM: 4 jobs    Scheduling period: 10 days

Con cap	1	# of Robots		
		2	3	
% machine utilization				
1	.6722	.6777	.6821	
	.5825	.5558	.5625	
	.3381	.2908	.2919	
2	.8085	.8029	.8110	
	.7789	.7760	.7696	
	.7059	.7155	.6989	
>2	.8055	.8150	.8075	
	.7905	.8029	.7858	
	.7050	.7370	.7165	

# WEIGHT vs MEAN LATENESS

## 3&4 JOBS 10&20 DAYS

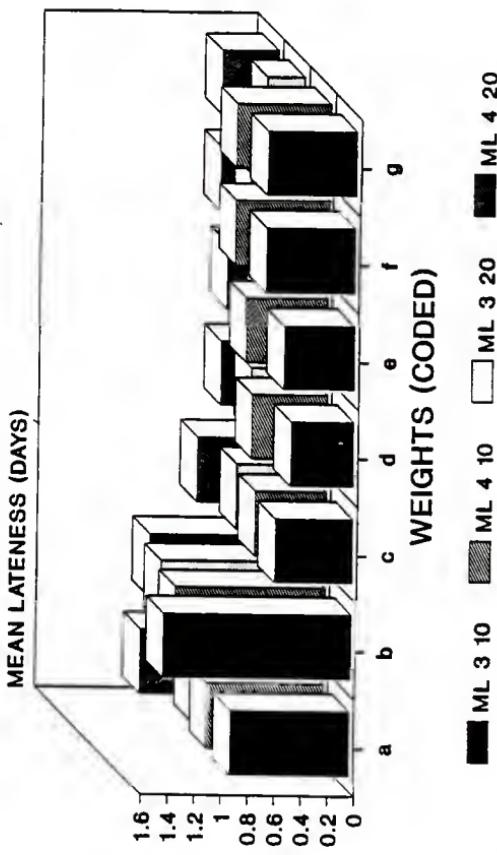


FIGURE 1

# WEIGHT vs MEAN LATENESS

## 3 & 4 JOBS 20 DAYS

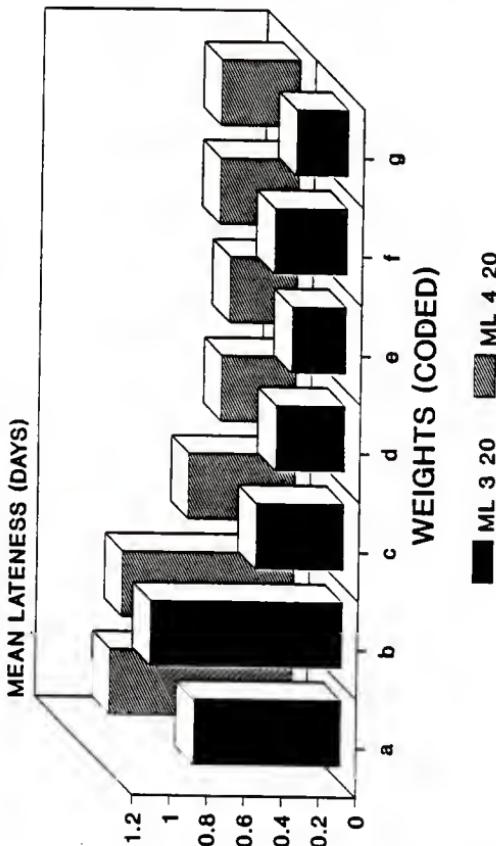


FIGURE 2

# WEIGHT vs UTILIZATION %

## 3 JOBS vs 4 JOBS



FIGURE 3

# RELATIVE TIME UTIL

3 JOBS

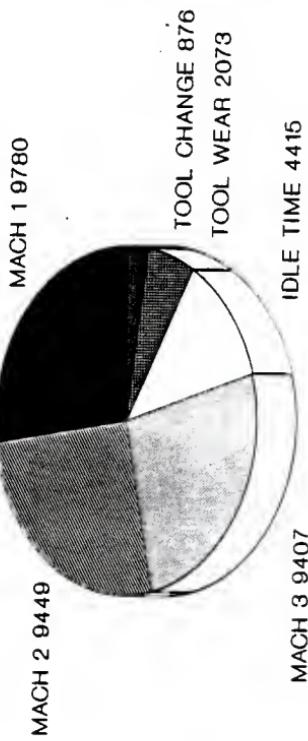


FIGURE 4

# RELATIVE TIME UTIL 4 JOBS

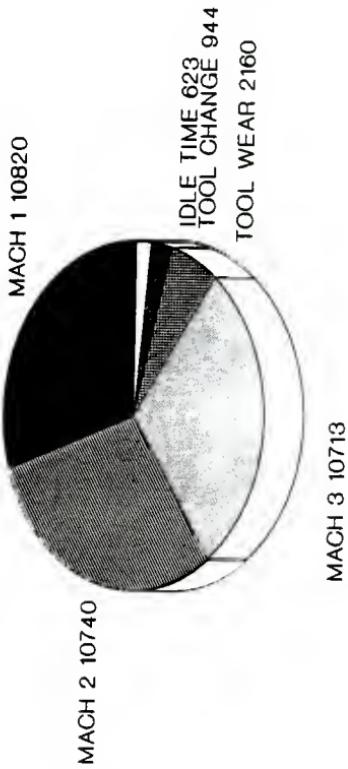


FIGURE 5

# RELATIVE TIME UTIL 5 JOBS

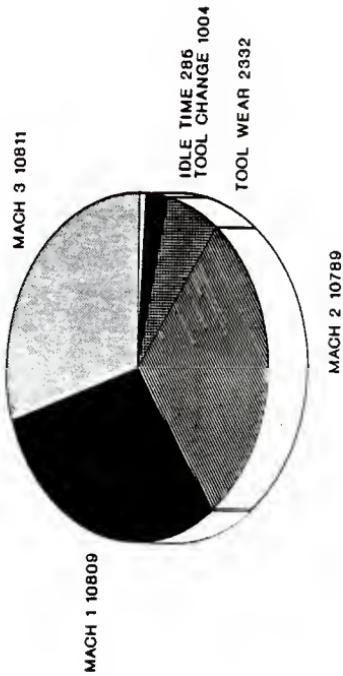


FIGURE 6

# WEIGHT vs UTILIZATION MACHINewise

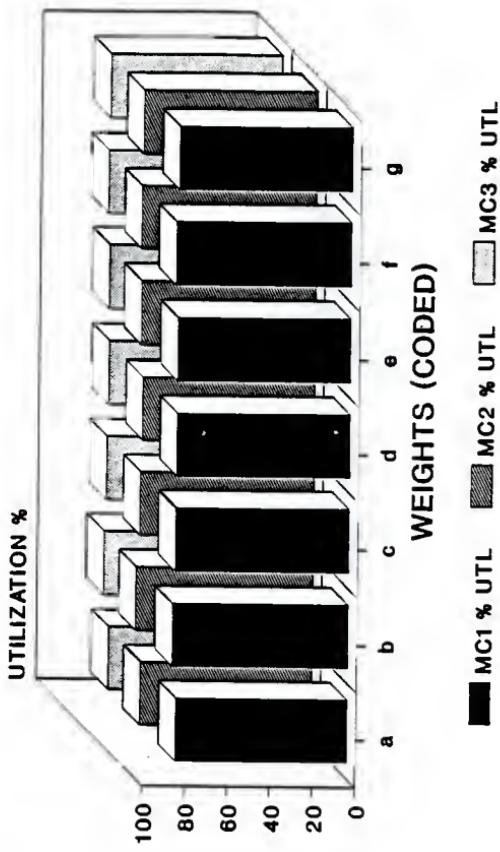


FIGURE 7

# WEIGHT vs MC UTILIZATION %

## 3 & 4 JOBS 10 & 20 DAYS

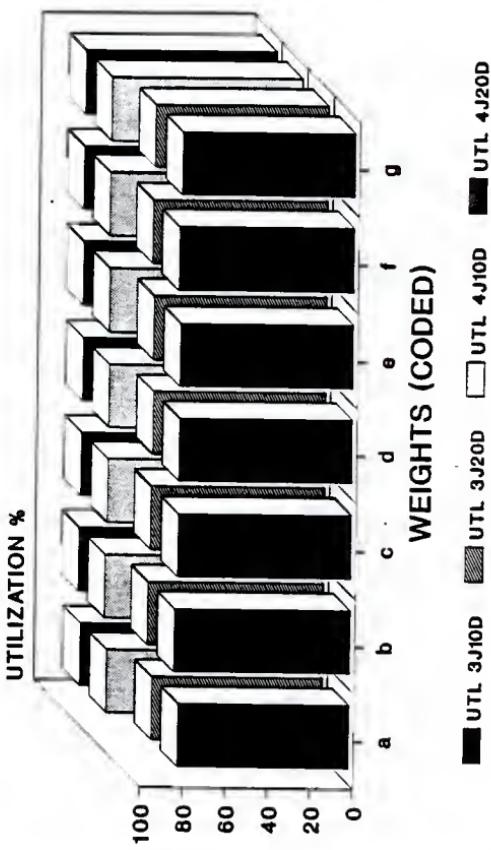


FIGURE 8

# LOAD vs UTILIZATION

## 10 vs 20 DAYS

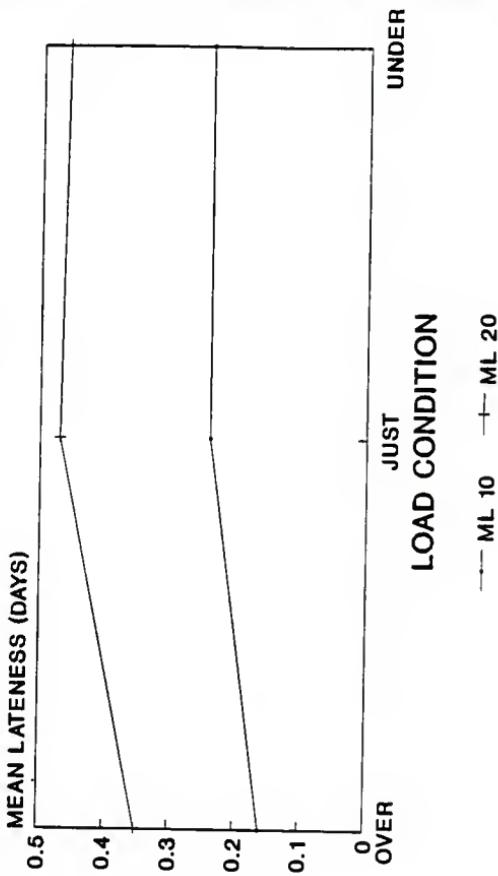


FIGURE 9

# LOAD vs UTILIZATION %

## 10 vs 20 DAYS

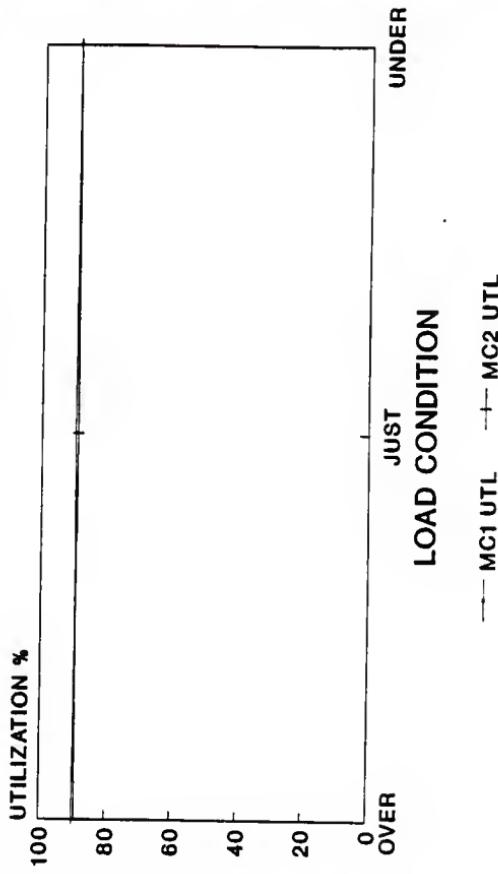


FIGURE 10

## EFFECT OF CONVEYER CAP ON MACHINE UTILIZATION

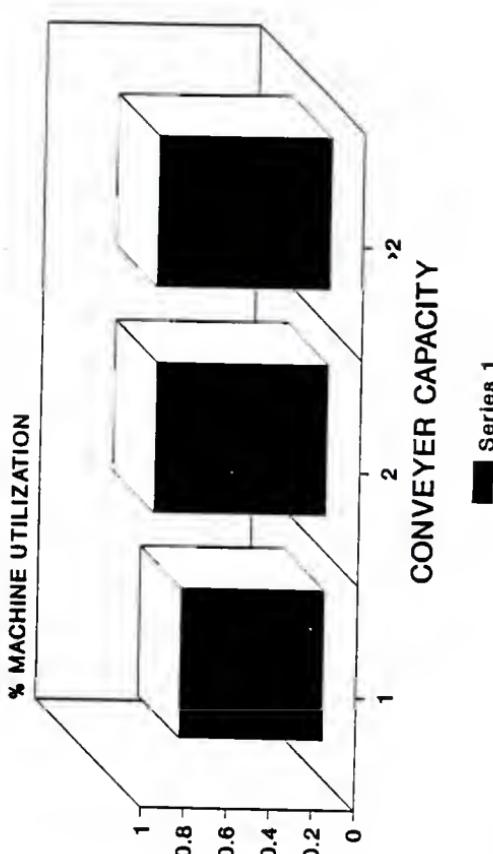


FIGURE 11

FLEXIBLE MANUFACTURING SYSTEM LAYOUT

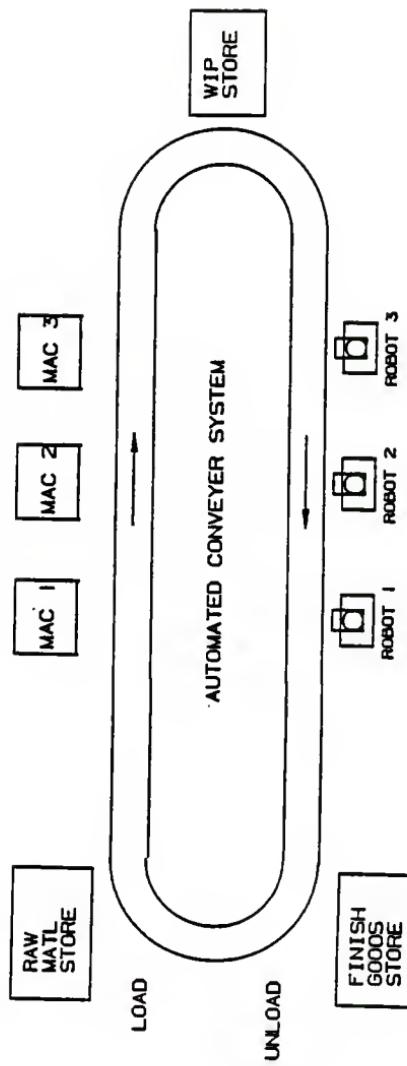


FIGURE 12

## CHAPTER X

### CONCLUSIONS AND RECOMMENDATION

In this chapter we present the conclusion to our thesis work and also the recommendations for further studies on this subject. During the course of analysis and validation of the simulated flexible manufacturing system, we noticed some of the shortcomings of this simulation. These are discussed at the end of the chapter.

#### 10.1 CONCLUSIONS

1. TOPSIS is one of the scheduling algorithms; that could be used for the due date objective. Weights improve the due date performance.
2. Nonmachining time due to tooling aspects is an important factor in studying the performance of the FMS. It accounts for 10-12% of the total time. The assumptions regarding tooling aspects in past research on flexible manufacturing systems needs to be investigated.
3. Capacity constraints on the material handling system is the important factor. By increasing the capacity of the conveyor from 1 part to 2 parts, the machine utilization improved by 12%.
4. Having an extra job waiting to seize a free machine

gives a better due date performance and higher machine utilization. The machine utilization increased by 10% with the 4-job policy compared to the 3-job policy.

5. Overloading the system helps to maintain an uniformly higher machine utilization.

## **10.2 RECOMMENDATIONS**

After studying and analyzing the performance of the simulated flexible manufacturing system, and the scheduling algorithm we make the following recommendations for further studies:

1. The effect of different part mixes was not studied in this thesis. This factor needs to be studied in detail to confirm the universality of the scheduling algorithm.
2. Tool scheduling was not given due importance in this thesis. We recommend that the topic of tool scheduling be pursued as a research topic. For a large number of parts and more machines in the flexible manufacturing system, tool scheduling is important. Tool scheduling affects the tool change time due to tool wear. This also calls for tool crib management considerations.
3. Machine utilization should be studied with real world machining times and parts.
4. We also recommend the detailed study of the effect of keeping the flexible manufacturing system overloaded,

just loaded, or underloaded.

### **10.3 SHORTCOMINGS OF THE SIMULATION**

The following shortcomings were noticed in this research. We mention these at the end of this thesis to guide future research in this area.

1. The actual machine scheduling has been carried out independent of the master production schedule, which may not be realistic.
2. The scheduling system used is a forward scheduling system in which the jobs arrive faster than possible processing. The excess jobs are discarded and the system is empty to start with. Instead, these could be treated as jobs for the next scheduling period. This would have taken care of the effects of starting empty.
3. The available time for the three machines is lumped into one number and required time is subtracted from the number as the jobs are accepted and assigned due dates. This forced us to make some unnatural round-off rules. Precision could have been obtained at the end of the period by maintaining an available time counter for each machine.
4. The time counter is set to zero at the beginning. Thus if the jobs do not arrive early (which is the case here), statistical fluctuations leads to the

overloading of system. An algorithm that will measure the actual available machining time could be used, along with initializing the simulation program with parts to manufacture.

We record these shortcomings in this thesis as a part of our effort to make this research more realistic and true to industry. We hope these will guide future research right from the start.

## REFERENCES

Akella, R., Choong, Y., Gershwin, S., "Performance of hierachial production scheduling policy", IEEE Transactions on Components, Hybrids and Manufacturing Technology, Vol Chmt-7, No 3, 227-241, 1984.

Ammons, C., and Lofgren, B., "A large scale machine loading problem in flexible assembly", Annals of Operations Research, 3, 319-332, 1985.

Bruno, G., and Conterno, R., "Hybrid simulation of a flexible manufacturing system", Advances in Production Management systems, E. Szelke and J. Browne, editors, 131-143, 1985.

Carrie, A. S., "Role of simulation in FMS: Methods and Studies", Elsevier Science Publication B. V. (North Holland), 1982

Carrie, A. S. and Perera, D. T. S., "Work scheduling in FMS under tool availability constraints", International Journal of Production Research, Vol 24, No 6, 1299-1308, 1986.

Chang, Y. L., Sullivan, R. S., Bagchi, U., Wilson, J. R., "Experimental investigation of real-time scheduling in

flexible manufacturing system", Annals of Operations Research, 3, 355-377, 1985.

Choi, R. H., and Malstrom, E., "Physical simulation of work scheduling rules in a flexible manufacturing system", Computers and Industrial Engineering, Vol 7, 390-394, 1986.

Chung, C., "Loading flexible manufacturing systems: A heuristic approach", Proceedings of 8th Annual Conference on Computers and Industrial Engineering, 246-250, 1986.

Fox, K., "Simulation for design and scheduling of flexible manufacturing systems", AUTOFACt4 CONFERENCE 1982.

Gershwin, S. B., Akella, R., and Choong, Y. H., "Short term production scheduling of an automated manufacturing facility", IBM Journal of Research and Development, Vol 29, No 4, 1985.

Hall, N., "Scheduling problems with generalized due dates", IIE Transactions, 220-222, 1986.

Hwang, S., "A constraint directed method to solve the part selection problem in flexible manufacturing systems

planning stage", Proceedings of the Second ORSA/TIMS Conference on flexible manufacturing systems planning stage, 297-309, 1986.

Iwata, K., and Murotsu, A., "Production Scheduling of flexible manufacturing systems", Annals of CIRP, Vol/31/1/1982, 319- 322, 1982.

Kiran, A., and Smith, M. L., "Simulation studies in job shop scheduling - I A Survey, Computers and Industrial Engineering, Vol 8, No 2, 87-93, 1984.

Kiran, A., and Smith, M. L., "Simulation studies in job shop scheduling - II Performance of priority rules", Computers and Industrial Engineering, Vol 8, No 2, 95-105, 1984.

Kusiak, A., "Application of Operational Research Models and techniques in flexible manufacturing systems", European Journal of Operational Research, Vol 24, 336-345, 1986..

Kusiak, A., "Artificial Intelligence and Operations Research in FMS", INFOR, Vol 25, No 1, 2-12, 1987.

Kusiak, A., "Designing expert systems for scheduling of automated manufacturing", Industrial Engineering, 42-46, 1987.

Lin, L. S., "Development and Analysis of Integrated real time scheduling methods for FMS with different storage layout", International Journal of Policy and Information, Vol 10, No 1, 67-82, 1986.

Nakamura, N., and Salvandy, G., "A experimental study of human decision making in computer based scheduling of FMS", Report of School of Industrial Engineering, Purdue University, 1986.

O'Grady, P. J., and Menon, U., "A concise review of F. M. S. literature", Computers in Industry, Vol 7, 155-167, 1986.

Oren, S., and Seidmann, A., "Analysis of flexible manufacturing systems with priority scheduling: PMVA", Annals of Operations Research, 3, 115-139, 1985.

Ravikumar K., Kusiak, A., and Vannelli, A., "Grouping problems in flexible manufacturing systems", Robotica, Vol 3, 244-252, 1985.

Rochette, R., and Sadowski, P. R., "A statistical comparision of the performance of simple dispatching rules for a particular set of job shops", International Journal of Production Research, Vol 14, No 1, 63-75, 1976.

Schriber, T. J., and Stecke, K. E., "Machine utilization and production rates achieved by using balanced aggregate FMS production ratios in a simulated setting", Proceedings of the second ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications, 405-416, 1986.

Shanker, K., and Tzen, Y. J., "A loading and dispatching problem in a random F. M. S.", International Journal of Production Research, Vol 23, No 3, 579-595, 1985.

Stecke, K. E., and Solberg, J. S., "Loading and Control policies for a FMS", International Journal of Production Research, Vol 19, No 5, 481-490, 1981.

Stecke, K. E., "Formulation and solution of non-linear integer production planning problems for FMS", Management Science, 273-288, March 1983.

Stecke, K. E., "Design Planning, Scheduling and Control problems of F. M. S.", Annals of Operations Research, 3, 3-12, 1985.

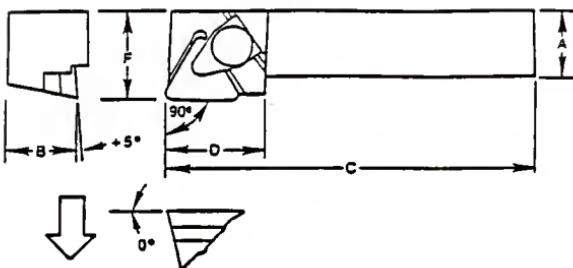
Stecke, K. E., and Berrada, M., "A branch and bound approach for machine load balancing in flexible manufacturing systems", Management Science, Vol 32, No 10, 1316-1335, 1986.

Steffen, M. S., "A survey of artificial intelligence based scheduling system", 1986 Fall Industrial Engineering Conference Proceedings, 395-405, 1986.

Vaithianathan, R., "Scheduling in flexible manufacturing systems", 1982 Fall Industrial Engineering Conference Proceedings, 1982.

Whitney, C. K., and Gaul, T. S., "Sequential decision process for batching and balancing in FMS", Annals of Operations Research, 3, 301-316, 1985.

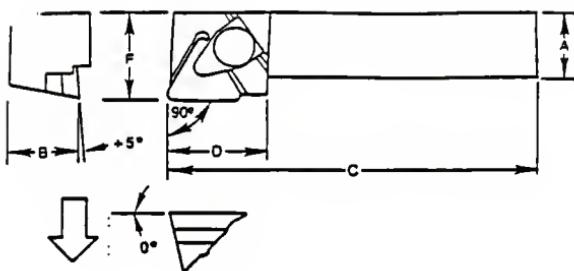
APPENDIX 2



**Part type 1**  
**DIMENSIONS:**      A: 1.00    B: 1.00    C: 5.00

**OPERATION**

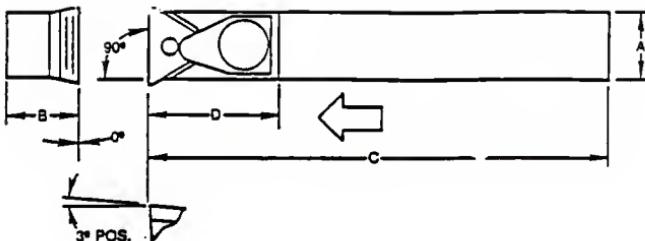
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (SIDE 1)	2	12	1	3"
2	Face milling (SIDE 2)	2	12	1	3"
3	Face milling (SIDE 3)	2	12	1	3"
4	Face milling (SIDE 3)	2	12	1	3"
5	End milling	-	66	3	APD
6	Drilling	-	5	4	APD
7	Tapping	-	2	4	APD



**Part Type 2**  
**Dimensions:** A: 1.50 B: 1.50 C: 7.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (SIDE 1)	2	15	1	3"
2	Face milling (side 2)	2	15	1	3"
3	Face milling (side 3)	2	15	1	3"
4	Face milling (side 4)	2	15	1	3"
5	End milling	-	66	3	AFD
6	Drilling	-	5	4	AFD
7	Tapping	-	2	4	AFD

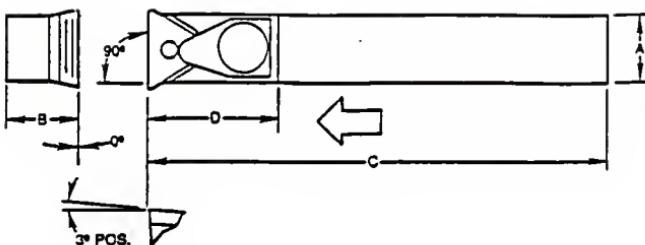


**Part type 3**

**Dimensions:** A: 1.00 B: 1.00 C: 6.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	14	1	3"
2	Face milling (side 2)	2	14	1	3"
3	Face milling (side 3)	2	14	1	3"
4	Face milling (side 4)	2	14	1	3"
5	End milling	-	46	3	APD
6	Drilling	-	5	4	APD
7	Tapping	-	2	4	APD



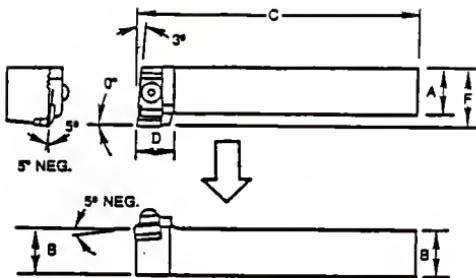
**Part type 4**

**Dimension**

A: 0.75    B: 1.00    C: 8.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	18	1	3"
2	Face milling (side 2)	2	18	1	3"
3	Face milling (side 3)	2	18	1	3"
4	Face milling (side 4)	2	18	1	3"
5	End milling	-	36	3	AFD
6	Drilling	-	5	4	AFD
7	Tapping	-	2	4	AFD

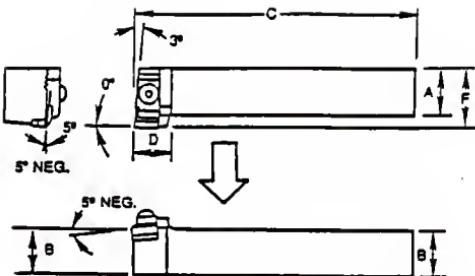


**Part type S**

**Dimensions:** A: 1.00 B: 1.50 C: 8.00

**OPERATION**

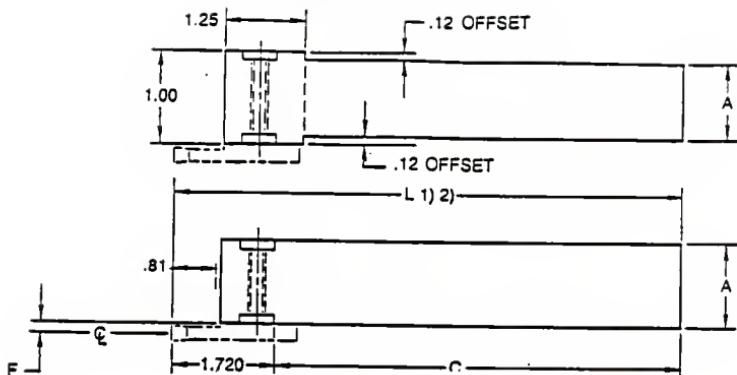
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	18	1	.7"
2	Face milling (side 2)	2	18	1	.7"
3	Face milling (side 3)	2	18	1	.7"
4	Face milling (side 4)	2	18	1	.7"
5	End milling	-	87	3	AFD
6	Drilling	-	5	4	AFD
7	Tapping	-	2	4	AFD



**Part type 6**  
**Dimensions**      A: 1.25    B: 1.50    C: 8.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	14	1	3"
2	Face milling (side 2)	2	14	1	3"
3	Face milling (side 3)	2	14	1	3"
4	Face milling (side 4)	2	14	1	3"
5	End milling	-	66	3	AFD
6	Drilling	-	5	4	AFD
7	Tapping	-	2	4	AFD

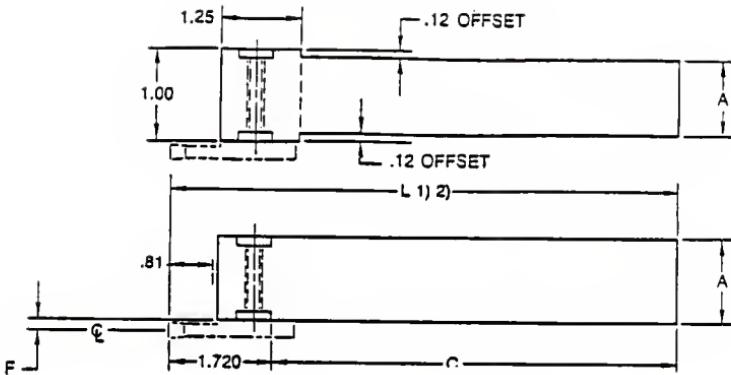


**Part type 7**

**Dimensions**      A: 1.25    B: 1.50    L: 8.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	18	1	.2"
2	Face milling (side 2)	2	18	1	.2"
3	Face milling (side 3)	2	18	1	.2"
4	Face milling (side 4)	2	18	1	.2"
5	End milling	-	56	2	APD
6	Drilling (side 1)	-	5	4	APD
7	Drilling (side 2)	-	5	4	APD
8	Tapping	-	2	4	HFD

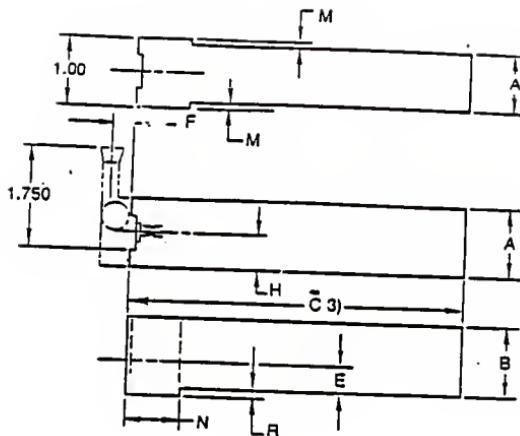


**Part type B**

**Dimensions:** A: 1.50 B: 1.25 L: 7.00

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	16	1	2"
2	Face milling (side 2)	2	16	1	2"
3	Face milling (side 3)	2	16	1	2"
4	Face milling (side 4)	2	16	1	2"
5	End milling	-	44	3	APD
6	Drilling (side 1)	-	5	4	APD
7	Drilling (side 2)	-	5	4	APD
8	Tapping	-	2	4	APD

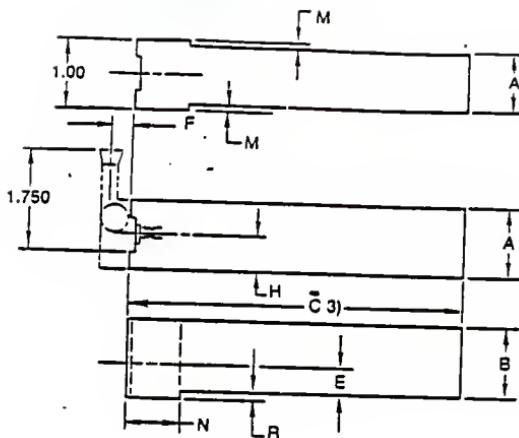


**Part type 9**

**Dimensions**      A: 1.50    B: 1.50    C: 8.0

**OPERATION**

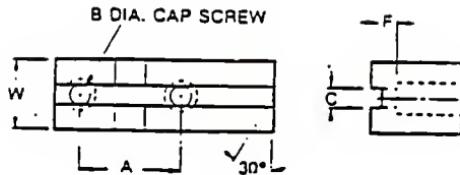
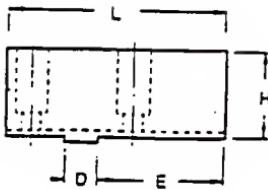
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	17	1	3"
2	Face milling (side 2)	2	17	1	3"
3	Face milling (side 3)	2	17	1	3"
4	Face milling (side 4)	2	17	1	3"
5	End milling	-	46	3	APD
6	Drilling (side 1)	-	5	4	APD
7	Drilling (side 2)	-	5	4	APD
8	Tapping	-	2	4	APD



Part type 10  
Dimensions      A: 1.0      B: 1.0      C: 6.0

**OPERATION**

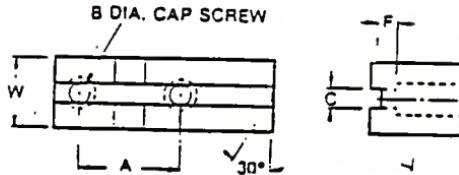
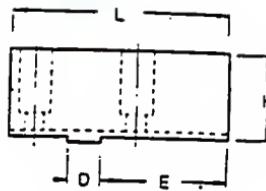
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	2	14	1	3"
2	Face milling (side 2)	2	14	1	3"
3	Face milling (side 3)	2	14	1	3"
4	Face milling (side 4)	2	14	1	3"
5	End milling	-	32	3	APD
6	Drilling (side 1)	-	5	4	APD
7	Drilling (side 2)	-	5	4	APD
8	Tapping	-	2	4	APD



Part type II  
Dimensions      W: 2.5    H: 4.75    L: 6.25

**OPERATIONS**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	12	1	5"
2	Face milling (side 2)	3	12	1	5"
3	Face milling (side 3)	3	12	1	5"
4	Face milling (side 4)	3	12	1	5"
5	End milling	-	48	3	APD
6	Drilling	-	8	4	APD
7	Tapping	-	3	4	APD



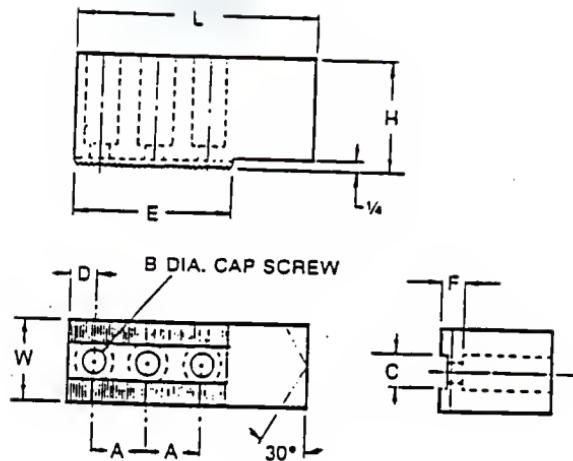
#### Part type 12

#### Dimensions

W: 1.5    H: 1.75    L: 3.25

#### OPERATION

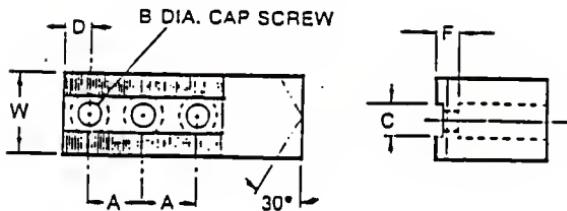
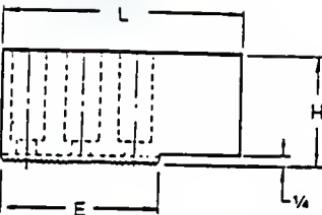
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	9	1	5"
2	Face milling (side 2)	3	9	1	5"
3	Face milling (side 3)	3	9	1	5"
4	Face milling (side 4)	3	9	1	5"
5	End milling	-	36	3	AFD
6	Drilling	-	8	4	APD
7	Tapping	-	3	4	AFD



**Part type 13**  
**Dimensions**      W: 1.75    H: 4.0    L: 6.625

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	16	1	5"
2	Face milling (side 2)	3	16	1	5"
3	Face milling (side 3)	3	16	1	5"
4	Face milling (side 4)	3	16	1	5"
5	End milling	-	42	3	APD
6	Drilling	-	6	4	APD
7	Tapping	-	3	4	APD

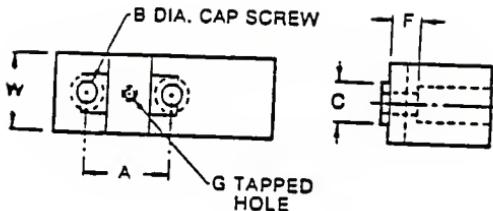
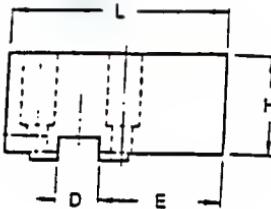


**Part type 14**

**Dimensions:** W: 1.25 H: 3.5 L: 4.25

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	13	1	5"
2	Face milling (side 2)	3	13	1	5"
3	Face milling (side 3)	3	13	1	5"
4	Face milling (side 4)	3	13	1	5"
5	End milling	-	35	3	APD
6	Drilling	-	8	4	APD
7	Tapping	-	7	4	APD



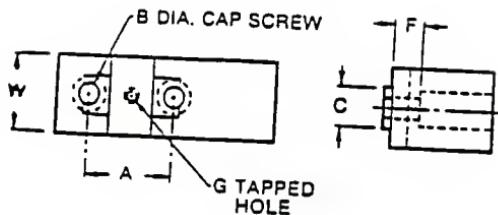
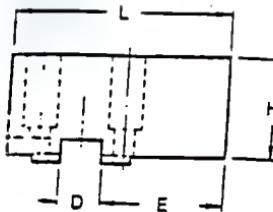
**Part type 15**

**Dimensions**

W: 3.0    H: 3.25    L: 6.0

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	16	1	5"
2	Face milling (side 2)	3	16	1	5"
3	Face milling (side 3)	3	16	1	5"
4	Face milling (side 4)	3	16	1	5"
5	End milling	-	42	3	APD
6	Drilling	-	6	4	APD
7	Tapping	-	3	4	APD



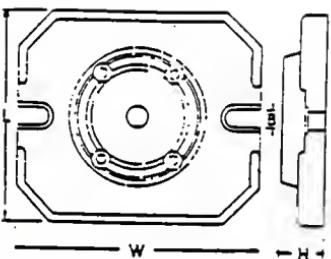
#### Part type 16

#### Dimensions

W: 1.75    H: 2.50    L: 4.125

#### OPERATION

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	3	14	1	5"
2	Face milling (side 2)	3	14	1	5"
3	Face milling (side 3)	3	14	1	5"
4	Face milling (side 4)	3	14	1	5"
5	End milling	-	35	3	APD
6	Drilling	-	8	4	APD
7	Tapping	-	3	4	APD

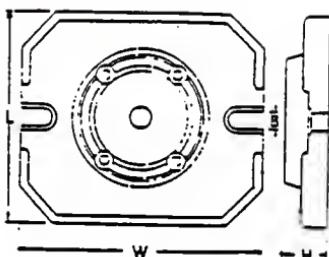


**Part type 17**

**Dimensions**            W: 11.32 L: 10.62 H: 1.25

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	4	55	2	12"
2	Face milling (side 2)	4	55	2	12
3	End milling & U groove mig	5	130	3	APD

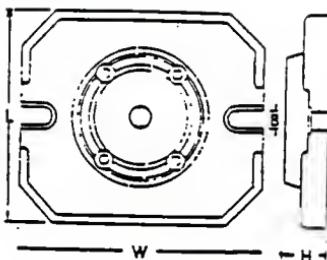


**Part type 18**

**Dimensions** W: 13.78 L: 12.5 H: 1.32

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	4	70	2	15"
2	Face milling (side 2)	4	70	2	15"
3	End milling & U groove mfg	5	140	5	APD



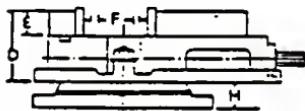
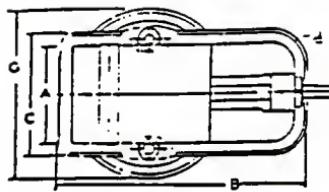
**Part type 19**

**Dimensions**

W: 15.75 L: 14.56 H: 1.44

**OPERATION**

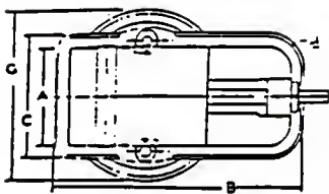
#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling (side 1)	4	80	2	15"
2	Face milling (side 2)	4	80	2	15"
3	End milling & U groove mig	5	150	3	APD



Part type 20 [ ONLY FACE MILLING]  
Dimensions B: 10.12 C: 4.5 D: 2.875

OPERATION

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling	2	38	2	12"
2	Face milling	2	38	2	12"
3	Face milling	2	38	2	12"
4	Face milling	2	38	2	12"

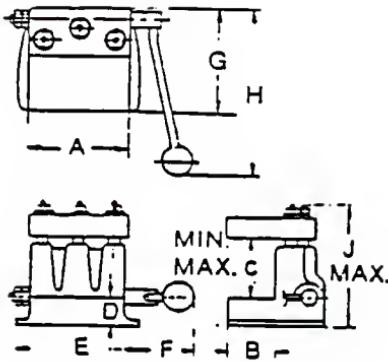


Part type 21

Dimensions      B: 12.56 C: 5.75 D: 3.375

OPERATION

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1	Face milling	2	45	2	15"
2	Face milling	2	45	2	15"
3	Face milling	2	45	2	15"
4	Face milling	2	45	2	15"



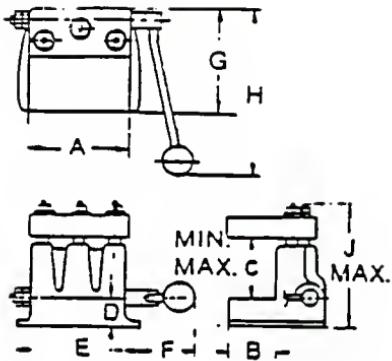
**Part type 22**

**Dimensions**

A: 4.0      G: 3.87      J: 7.625

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1-4	Face milling (base plate)	8	40	2	.12"
5-8	Face milling (top plate)	8	40	2	.12"
9-12	Face milling (rear plate)	8	40	2	.12"
13	End milling & others	-	20	3&4	AFD

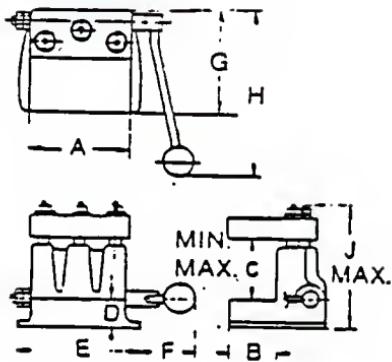


**Part type 23**

**Dimensions**      A: 5.0      G: 4.93      J: 8.96

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1-4	Face milling (base plate)	8	40	2	12"
5-8	Face milling (top plate)	8	48	2	12"
9-12	Face milling (rear plate)	8	40	2	12"
13	End milling & others	-	30	3&4	APD

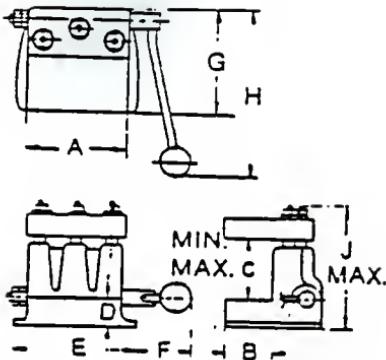


**Part type 24**

**Dimensions**      A: 6.0      G: 7.57      J: 11.5

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1-4	Face milling (base plate)	8	48	2	12"
5-8	Face milling (top plate)	8	56	2	12"
9-12	Face milling (rear plate)	8	48	2	12"
13	End milling & others	-	25	7/4	APD



**Part type 25**  
**Dimensions**

A: 8.0    G: 10.5    J: 14.12

**OPERATION**

#	Description	ST	MT	TOOL GROUP	TOOL DIA
1-4	Face milling (base plate)	8	64	2	12"
5-8	Face milling (top plate)	8	68	2	12"
9-12	Face milling (rear plate)	8	48	2	12"
13	End milling & others	-	20	3&4	APD

SCHEDULING OF A FLEXIBLE MANUFACTURING SYSTEM  
FOR BICRITERION OBJECTIVE: TARDINESS AND UTILIZATION

BY

THALLI K. BADRINATH

B. E., Bangalore University, India, 1983

AN ABSTRACT OF A THESIS

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KANSAS STATE UNIVERSITY  
Manhattan, Kansas

1989

## ABSTRACT

Scheduling flexible manufacturing systems has been a topic of interest for research. Most researchers have looked at this problem, with the objective of:

- a. Maximizing machine utilization
- b. Minimizing number of machine visits for the parts.

In the majority of the work published, tooling aspects have been either ignored or assumed not important. Most flexible manufacturing machines use CNC machines, and tungsten carbide tools. Tungsten carbide tools have an average life of 30-45 minutes per insert. This would result in considerable tool changing. Meeting due dates was another objective that was ignored.

In this thesis we researched the above factors not considered important by others. Accordingly a flexible manufacturing system was simulated, and scheduled with the objective of:

- a. Meeting due dates
- b. Maximizing machine utilization.